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**DOI**
10.3390/architecture4030036

**Publication date**
2024

**Document Version**
Final published version

**Published in**
Architecture (MDPI)

**Citation (APA)**
Koutamanis, A. (2024). Stair Design and User Interaction. *Architecture (MDPI)*, *4*(3), 692-716.
https://doi.org/10.3390/architecture4030036

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# Stair Design and User Interaction

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**Abstract:** Stairs are among the key elements in architectural composition, both aesthetically and spatially. They are also one of the main innovations in architecture and building, allowing pedestrians to bridge considerable height differences with relative efficiency. It is, therefore, surprising that, in spite of all stair regulations in building codes, stairs are responsible for a huge number of accidents—second only to motorcars. The extent of safety failures suggests that user interaction with stairs is poorly understood by designers and policy makers. This is not unrelated to the lack of research into the design and use of stairs. Templer's seminal work is the exception, but it dates from 1992, and since then, little has been done to understand the relation between architectural design and stair performance, including safety. The paper reviews the literature on stairs in multiple domains and proposes that to redress poor stair performance, research and practice should build on affordance-based analyses of stair climbability, which establish a clear connection between the form of a stair and the perception of both action possibilities and dangers by all kinds of users. By doing so, affordances establish a comprehensive and consistent framework for the analysis of architectural designs, which utilizes both domain and psychological knowledge, including as a foundation for computational applications.

**Keywords:** interaction; safety; affordances

**Citation:** Koutamanis, A. Stair Design and User Interaction. *Architecture* **2024**, *4*, 692–716. https://doi.org/10.3390/architecture4030036

Academic Editor: Vincenzo Sapienza

Received: 25 April 2024
Revised: 17 August 2024
Accepted: 26 August 2024
Published: 5 September 2024

## 1. Introduction: The Trouble with Stairs

### *1.1. Pride and Fall*

With their multiple symmetries, continuity, and penetrative form, stairs are one of the most eye catching and photogenic parts of any building. They are also key elements in the spatial composition of buildings and landscapes; they provide subtly regulating means for connecting and experiencing architecture in all tendencies and styles [1]. Equally significantly, they are one of the major innovations of architecture, one that does not merely amplify our existing capacities but actually gives us new abilities [2] to move between floors with a considerable height difference in relative comfort. It is an ability for which there was no real alternative until relatively recently, when lifts and escalators entered the picture. It is, therefore, not accident that the history of stairs is studded with significant contributions to architecture in general [1].

At the same time, stairs are the location of an alarmingly large number of injuries. A study established that, over a 23-year period, more than a million stair-related injuries are treated annually on average in US emergency departments. Of these, approximately 32% were sprains and strains, 24% were soft-tissue injuries, and 19% were fractures. In roughly 42% of the cases, the injuries were in the lower extremities, and in almost 22%, in the head and neck [3]. Other sources report more than 1.23 million non-fatal injuries on stairs in 2009–10, resulting in 12,000 deaths, with a total cost exceeding USD 92 billion. This makes stair-related falls first among the causes of non-fatal injuries related to consumer products in the USA [4,5]. Only motor vehicle-related fatalities are higher (45,000 annually). Remarkably, while deaths from fire or burns are 5000 per year, fire safety receives much more attention than stair safety [6].

In other countries, such as the UK, out of 1035 deaths related to building features in coroners' reports in a year, 80% were attributed to falls and 61% to falls on stairs. A total of 514 accidents were on stairs and only 56 were on the seemingly more precarious steps and ladders [7]. According to other sources, the annual numbers for falls on stairs in the UK were 230,000–290,000 serious accidents and 500–600 fatalities (out of a total of 4000) at home, plus 100,000 accidents and 1000 fatalities during leisure activities outside the home. In total, 29% of all falls occurred on stairs [8,9]. In a single A&E department of a Dutch academic hospital, 464 patients were treated for stair-related falls in 2005. Out of these, 61% required admission, and two died, both with severe traumatic brain injury [10].

These numbers become even more alarming when one takes into account the limited risk exposure time, i.e., the relatively little time people spend on stairs [11]. The critical role of stairs in emergencies, such as fire egress, also reinforces this concern [12]. Similarly worrying is that most stair-related injuries are caused on private stairs [13], which have lower standards than public ones and are less rigorously regulated and maintained. It is also contradictory and ultimately ironic that stair walking is promoted and studied as an accessible health exercise and measure [14–20], although in-depth analyses conclude that the current stair design does not meet the needs of vulnerable users [21]. In UK coroners' reports (at least the ones that bothered to include environmental data), falls were not on bad or too long stairs; 30% had at least one handrail, while 25% were on flights with 13 steps and almost 18% were on flights with 14 steps [7]. This suggests that current codes are far from adequate and that stair failure is not easy to explain within the current design and regulatory mindset.

A defensive response would be to put the blame on stair users. Indeed, there is evidence that many people adopt risky strategies from walking on stairs too absorbed in their smartphones [22] to walking with small and variable foot clearance from step nosings [23]. Human error is an inevitable factor in hazards, and people should certainly be educated and reminded to use stairs with due care and attention. However, this should also be coupled with the provision of all necessary safety and efficiency features in the stairs and their immediate environments. Regardless of who is to blame, the problem clearly lies in user interaction with stairs; therefore, also in the understanding of this interaction by designers and policy makers. In the age of inclusiveness and equity, stairs should surely be as safe as possible for all users young and old, slow or fast, strong or weak, sober or inebriated. Their design should prevent and anticipate the slips and stumbles that form the starting point of disastrous stair falls, as well as minimize the effects of such falls. They should also allow users to perceive directly how they should walk on stairs safely and effectively.

### *1.2. Action Identification and Affordances*

The last point is important to this paper. As Action Identification Theory (AIT) suggests, anything people do has multiple identities at various levels. An activity, e.g., going from A to B or writing a report, consists of one or more actions, such as going through doorways, walking on stairs, or using a computer and a text processing program. Each action normally contains several operations, for example, holding a handrail or tapping on a keyboard [24]. The higher levels provide an understanding of our objectives—what we are doing, its reasons, effects, and implications—and the lower ones concern the specifics of what we do and especially how we do it. When both higher and lower identities are available, the higher ones tend to be prepotent; while walking on a stair, we think of our destination and what might expect us there, letting our hands and legs do the walking without conscious control. If something cannot be performed with reference to a higher identity, the lower ones take over. A slippery or unequal step, a painful knee, or the absence of a handrail shifts our attention to the operations of stair walking, i.e., the precise interactions with features of the stair and possibly other current users of the stairs. In either case, what we do is maintained with respect to its current prepotent identity, which serves as the goal, intention, frame, and performance criterion. Preoccupation with higher or concurrent activities and the resulting cognitive load may distract from the lower-level actions and operations, and lead to stair accidents [25].

Stair walking is something we normally do automatically, without conscious attention to the features that may be relevant to our safety and our interactions with them, but this does not mean that we are unaware of these features. The theory of affordances argues that an environment presents specific action possibilities to a particular animal. These are perceived directly, without the mediation of mental representations, so that they can be acted upon automatically [26,27]. Users perceive the climbability of a stair (the how is discussed in a later section) and proceed to walk on it, normally without conscious control of how feet land on the steps or hands glide along the handrails. This allows them to preserve precious cognitive capacities for higher matters, such as the purpose of their going from A to B.

Affordances can be positive or negative; stairs allow pedestrians to bridge considerable heights but are also hazardous because they contain a great number of hard edges in sequences that make falls more painful and dangerous than falls on level surfaces. We normally perceive both positive and negative affordances on a gradient; the closer to the edge, the greater the danger [26]. This explains why walking speed on stairs is significantly lower than on level walkways, 30 m/min in ascent and 37 m/min in descent, which would be shuffling speed on a level walkway, where free flow is at 91 m/min [6].

Perception of affordances and the execution of relevant operations and actions are moreover direct; in dual-process theory terms [28–30], they are Type 1 processes, which are autonomous, unconscious, automatic, fast, and low effort. Examples of such processes are simple mental calculations, such as 2 + 3, the recognition of a common animal species, like a dog, or grasping a handrail. By contrast, Type 2 processes are controlled, analytical, slow, and high effort; for example, demanding mental calculations, such as $3647 \times 6387$, filling in an insurance form for a motor vehicle accident, or planning a route to an unfamiliar place. Walking on stairs is performed through Type 1 repetitive actions, which explains why, e.g., step regularity is so important for safety. If the perception of affordances proves erroneous or actions fail to produce the expected results, users may scrutinize the environment and themselves more closely. For example, they may choose to adapt their gait, use the handrails to stabilize themselves and prevent or soften a fall, or simply stop walking. Suddenly, what takes place automatically becomes the subject of Type 2 thinking; actions, and especially operations, become an objective by themselves and an opportunity for learning new affordances from them. In other words, it is not always out of stupidity that people fall on stairs but quite often for reasons of cognitive economy.

Affordances are a promising approach to studying the interaction between stairs and their users. For one, affordances concern whole actions and whole environments and, therefore, connect different local interactions, such as holding on handrails, landing feet on steps, and perceiving step edges. They link the various levels of AIT in a way that transparently integrates all relevant aspects and factors into overall possibilities for action, as well as positive and negative outcomes [31,32]. These possibilities are matched to the individual effectivities (capacities for action) of a user [33], which derive jointly from their body and action potential. Consequently, affordances approach interaction and usability as variable, dynamic processes that go beyond basic ergonomics [31,34] and help explain differences between the intentions behind a design and its actual use [32,35–38].

Interestingly, stairs have been one of the earliest subjects investigated with respect to affordances and affordance perception. This established a long line of research into stair affordances (discussed in a later section) and produced a range of results from which we can learn about user interaction with stairs in order to improve stair comfort and safety.

### *1.3. Objective and Structure of the Paper*

The objective of the paper is to show how much is already known about stairs in design and safety studies and connect that to affordance research in order to define a coherent and comprehensive frame of user interaction with stairs. This allows us to go beyond the superficial and piecemeal box ticking of regulations and helps, firstly, understand the many essential aspects and features in stair design and their interconnections, and, secondly, which directions for further research are worth pursuing.

This is essential for both design and research because existing norms and codes that underlie the design and validation of stairs arguably are both insufficient and based on shaky foundations [6]. It is ultimately shocking that Blondel's less-than-useful formula (discussed in the section on stair design) is complacently retained in most building codes in the world and remains the basis for calculating stair geometry, while related key issues, such as going depth in relation to foot size, are ignored and others, such as adequate lighting and the presence and form of handrails, are downplayed. Apparently, a pseudoscientific justification counts for more than personal observation and experience with stair hazards, the differences between ascent and descent, and the variability of users. This is made even more embarrassing by the fact that objective evidence for such matters exists already from the end of the 19th century, when Muybridge produced high-speed photographic breakdowns of adults ascending and descending, as well as children walking and crawling on stairs [39].

To explain the current failure of stair design and the potential for improvement, the remainder of the paper starts from the domain of architectural design and then moves to related yet unconnected disciplines. Section 2 is an account of design treatises on stairs, with Templer's monumental work [1,6] as the centerpiece. Section 3 presents the results of safety studies, including the epidemiologic and ergonomic literature, completing what could be construed as wider domain knowledge. Then, the paper continues with a review of the affordance literature on stairs, starting with Warren's seminal paper [40], before discussing how the different bodies of knowledge combine to produce a rich collection of information that deserves more coherence, as well as better tools for utilization in design.

## 2. Stair Design

### 2.1. Design Textbooks and Codes

It is remarkable how few architectural publications, in particular, research papers, are on stair design. Despite the high number of accidents on stairs, it is apparently presumed that the subject of stair design is adequately covered by existing codes and domain knowledge. This certainly seems to be the perspective of most architectural textbooks on the design and construction of stairs. Emphasis varies between textbooks, but all are generally sensitive to comfort and safety, especially concerning critical conditions, like fire egress and certain categories of vulnerable users, such as disabled or elderly users [41]. Accidents caused by the design and the detailing of stairs, and dangers to children, such as horizontal boards that invite climbing, are clearly illustrated [42]. Textbooks are often also aware of the low safety record of stairs, e.g., in Germany in 1992, there were 60,000 accidents on stairs [43].

Concern for comfort and safety is not restricted to critical situations and vulnerable users; it is permanent and for all. For instance, textbooks stress that there should be adequate walking distance (at least 1800 mm) before the first riser and balustrades for protection on both sides [41], especially if the stair width is more than 1250 mm [42]. Such elements are deemed necessary not only for protecting users from falls but also for alarming them to stair and ramp dangers. Concerning this, not even architectural masterpieces are immune from scrutiny and criticism. Wright's Guggenheim Museum in New York has a much-admired spiral ramp at its core, but that ramp has a "low concrete balustrade. It does not prevent vertigo, although placed in a sloping plane and angled away from the ramp" [41]. Comfort and safety relate to many features of stairs with which users interact. Handrails, for example, are often considered in great detail, connecting construction to ergonomics [42]. Even the tactile quality of materials is considered. "The comfortable feel of timber to the touch should not be forgotten. Handrails are shaped to be grasped . . ." [41].

Underlying stair design is the overall stair geometry. In this respect, textbooks advise on the form and composition of stairs, e.g., that a direct flight should be limited to 16 risers.

Longer stairs should be broken by landings at 16-riser intervals [41]. Step dimensions are considered fundamental and invariably from building codes. These typically prescribe values for the maximal rise and minimal going (Table 1).

**Table 1.** Maximal rise and minimal going in the Dutch and British building codes.

| | Dutch | | British | | | |
|---|---|---|---|---|---|---|
| | **Residential** | **Other** | **Private** | **Comfortable** | **Institutional** | **Disabled, Elderly** |
| Going | 220 | 185 | 220 | 240 | 280 | |
| Rise | 188 | 210 | 220 | 190 | 180 | 170 |

Some codes, such as the British, emphasize the pitch of stairs as an indication of steepness, as well as a link between rise and going size. Other codes, e.g., the Dutch, assume a walkline at a distance of 300 mm from the side of the smaller going as an axis of human movement and measure going and rise along that line. Some textbooks suggest more generous sizes, for example, a walkline placed 450 mm from the center of the handrail or at the center of the going on narrower stairs [42].

Building codes also regulate headroom (at least 2000 mm in the British) and stair width. The latter usually depends on the use of the building and the stair; in the British code, escape stairs should be minimally 800 mm wide, common stairs in flats and assembly buildings 1000 mm, and if also used in firefighting, 1100 mm.

Dimensional constraints also apply to handrails; there should be one on at least one side of the stair at a height of 800–1000 mm (Dutch code) or 900–1000 mm (British code). The British regulations require handrails on both sides if stars are wider than 1000 mm. Guarding in the form of rails, balustrades, etc., should be included if the difference between levels is higher than 600 mm (British code) or 1000 mm (Dutch code).

Building codes also include topological and qualitative constraints. The British one stipulates that (a) the rise should be generally constant throughout the width of each step; (b) each step should be level and have a slip-resistant surface; (c) rise and going should be the same in a flight; and (d) stair nosings should be distinguished for the benefit of people with impaired sight.

The above indicates, first of all, that there are many features and factors involved in the affordances of stairs. Regulations and textbooks draw from user and professional experience and suggest norms and constraints, which become “magic numbers” without adequate justification [44]. They just seem reasonable and plausible, and so evade scrutiny. However, choices made in codes and professional standards should be transparent if designers are to understand and implement them, as well as for the continued evaluation and improvement of norms and guidelines [44]. For example, stair widths relate to pedestrian flows, so fire codes need to adapt them to demographic changes, such as population aging, which may reduce egress speed by 20% [45].

For some sizes, e.g., handrail height, the relation seems obvious and simple. Step dimensions, on the other hand, are less clearly derived. Most preferred sizes for going and rise seem reasonable, but the problem is that many textbooks and codes insist on linking them by means of the following formula invented by Blondel [46]:

$$\begin{gathered}2 \times \text{rise} + \text{going} = \text{human stride} \\ \text{(usually 600–700 mm)}\end{gathered} \tag{1}$$

The reasoning behind the formula is dubious, and its applicability is demonstrably limited to a small number of average sizes [6], yet its acceptance by professionals and policy makers remains remarkably and unshakenly universal. Even worse, it has inspired the development of competing formulae, such as [43] the following:

$$\text{going} - \text{rise} = 120 \text{ mm} \tag{2}$$

$$\text{going} + \text{rise} = 460 \text{ mm} \tag{3}$$

Reasonable step sizes, like 170 mm rise to 290 mm going, are considered acceptable because they satisfy all three formulae [43], even though the equations have never been validated. It appears that a simile of mathematical respectability suffices for architects and policy makers to believe in them.

Finally, design textbooks contain very little about the effectivities of users. The disabled and the elderly are mentioned but not analytically examined. Some lesser-known hazards, such as the lack of heel space in descent, are occasionally acknowledged and linked to nosings [42] but not systematically and unambiguously linked to the sizes and behaviors of users.

In conclusion, design textbooks are characterized by an analytical presentation of various aspects of stairs, invariably from the perspective of the designer. They are sensitive to safety and provide useful hints for it. In terms of sizes and features, they tend to refer to building codes, trusting the wisdom of the latter and focusing primarily on compliance.

### *2.2. Accessibility Textbooks*

Accessibility textbooks are also aimed at designers but, as they primarily cater to particular categories of users, they point out specific aspects, such as the different effectivities of people with impairments. Their recommendations, however, differ little from those of standard stair textbooks. For step dimensions, for example, they specify comfortable sizes as follows:

- Maximal rises of 150 mm for external or 185 mm for internal stairs [47] or 150–170 mm in general [48];
- Minimal goings of 300 mm for external or 230 mm for internal stairs [47] or 250–300 mm in general, with a preference for 300 mm [48];
- Minimal width of 1200 mm for external, 1000 mm for internal, and 1500 mm for internal stairs used for emergency egress [47].

Step dimensions remain subject to Blondel's formula and building codes, rather surprisingly keeping stride length at 600–650 mm [47]. Flight composition is kept comfortable, with recommendations of no more than 12 rises per flight or, at worst, 16 for small premises [48].

Accessibility textbooks justify many recommendations through stair gait characteristics that apply to all users. For example, inadequate goings make it impossible to put the whole of the foot on a tread, so as to support the weight of the body on the sole in ascent, or to place the heel on the tread in descent. This leaves users with the alternative of having to turn their foot sideways in order to obtain the necessary area of support. Similarly, they recommend that open rises or deeply recessed risers should be avoided because they can catch the toes or other parts of the foot, as well as be visually confusing. They also emphasize the significance of visual indications at the nosing of each step (in contrast with the rest of the step) [48].

Other recommendations are more specific to people with impairments, such as that the handrail is a means of not only support but also orientation for people with impaired vision or that there should be tactile indicators at the top and bottom of the stairs. All stairs, regardless of length, should have handrails on both sides, continuous and extending at least 300 mm beyond the stairs, supportive of the hand and the forearm, and be graspable. They should be 40–50 mm in diameter, with 50 mm of free space around them. Accessibility textbooks also add compulsory components and details, such as a second handrail at a height of around 600 mm for smaller people and children, and nosings with an angle of around 15% [47]. Projecting nosings are rejected, while nosing overlaps with the tread and is stipulated at 25 mm at most [48].

In summary, accessibility manuals provide a better understanding of user effectivities in order to sensitize designers to the plight of impaired users. They add detail to user interaction with stairs and provide insights into critical factors and the total effect of various, often interrelated factors. They are rather summary on dimensions, putting much faith in building codes, and rely on the designers' understanding of materials (e.g., for slip resistance) and compliance with codes. Factors relating to the operation of buildings (e.g., maintenance or lighting) receive little attention.

### *2.3. Templer's Conclusive Work*

If design and accessibility textbooks appear rather selective, Templer's monumental two volumes on the subject are the notable exception. The first is an architectural history of stairs [1]. It describes the evolution of stair types in relation to their times, such as how aesthetic, functional, and structural goals changed in different periods, following or even guiding wider architectural pursuits. By virtue of their monopoly on vertical circulation until the 20th century, stairs and ramps related to practically everything else in a building.

Architects are shown to be concerned with construction, locomotion, perception, and use in a comprehensive manner that goes beyond mere aesthetic or utilitarian principles. Two themes emerge: (a) stairs as an aspirational element that expresses power, authority, status, or prestige, and (b) stairs as a critical part of spatial composition, bringing different physical levels together or reversely separating them by acting as a bridge. The starting point is the fundamental difference between step geometries; small goings and large rises ask for a brisk gait, while larger goings and smaller rises suit a leisurely gait.

In any period, specific stair types serve as devices for emphasis, usually of status, e.g., external approach stairs in the Renaissance, helical stairs in medieval buildings, arguably more than others, the grand baroque stairs of the 17th and 18th centuries, and the bare-bones industrial-looking modernist stairs that provided a sharp contrast with heavy, decorated historicist staircases. Interestingly, grand stairs remained popular as aesthetic and status devices, even after reception rooms were moved from the first to the ground floor, i.e., even though visitors could not be impressed by the means of access.

The evolution of many stair types follows a common pattern: liberation from walls and ceilings so that stairs could become more visible (useful for ceremonial uses) but also provide better views of the rest of the environment. At the same time, stair components become embellished, usually with decoration but also with pronounced forms (geometry). For example, the continuity of handrails in helical stairs stresses the continuity of movement. Status and spatial considerations often fused; dogleg stairs in Renaissance gardens provided the functional and aesthetic means to bind several garden levels into a single composition and a continuous, controlled experience. Their success in doing so made them the inspiration for the great baroque interior stairs.

In summary, Templer's first volume helps understand the complexity of stair design in a structured and transparent manner, such as how functional considerations relate to use and purpose, how structural aspects constrain them (and hence are often modified to accommodate new ideas), and how spatial considerations contribute not just to the connections of stairs to other spaces but to the overall design of the building, too; stair design cannot be seen separately from the rest of the building.

The second volume [6] focuses on functional aspects. Templer starts his analytical and detailed examination of human interaction with stairs by stressing the responsibility of the building industry for the huge number of accidents on stairs. Stair safety should and could have been much higher, but he claims that this is not feasible with the current codes or without a better understanding of the many aspects of this admittedly complex problem. Regarding the causes, Templer does not separate but integrates; he asserts that stair falls relate to several factors that act singly or in concert. These factors result from (1) stair design, construction, and maintenance (e.g., single step, narrow goings, dimensional irregularity, inadequate illumination, rises too high or too low, slippery surfaces, things on stairs, no handrails, nosing strips that project above the tread, distracting patterns on treads); (2) the environment of the stairs (e.g., step or stairs in an unexpected place, distracting views); and (3) characteristics and behaviors of the stair users (e.g., hurry, distraction, carrying something or misjudgment). The more the factors present, the higher the likelihood of accidents.

Walking, even on level surfaces, is anyway risky because bipedal locomotion makes us constantly off balance. Walking on stairs is even worse because the intricate terrain of so many risers, nosings, and treads makes walking more difficult and the consequences of a fall more serious. To reduce the danger of a fall, people walk in an exaggerated gait on stairs, with increased precision and almost in slow motion and with repeating acceleration and deceleration and virtual stops as the foot lowers on a tread. As stair geometry controls movement more than a level walking surface, a safe and comfortable gait on stairs requires continuous and rhythmical motion. Walking too fast is avoided and is nearly as difficult as walking very slowly on stairs, which is very demanding and, hence, dangerous for weaker users and elderly adults. Moreover, Templer suggests that the gait differences between ascent and descent are such that if we had separate stairs for ascent and descent, the designs would have been quite different.

In descent, the leading foot swings forward over the nosing edge, with the toe pointing down. It then lands with the metatarsal heads on the tread below, while the heel of the following foot rises, transferring the body weight to the forward foot. This continues as the following leg bends at the knee and hip, controlling the fall, until the leading heel fully lands on the tread and the following leg becomes leading.

In ascent, the leading foot remains roughly horizontal as it lands on the next tread, making contact with the ball and optionally with the heel. Simultaneously, the following foot rises on tiptoe to lift the body upward and forward, pushing down and back against the tread. This makes it easier for the leading leg thigh to straighten the leg and lift the body. At the same time, the following leg swings forward to become leading.

Handrail use also differs between ascent and descent. In descent, the hand slides down the rail in a continuous motion that increases the sense of security and postural stability. Weaker users, who descend very slowly, may also use it as a crutch. In ascent, the handrail is grabbed at regular intervals and used to pull the user up, as well as to increase postural stability.

In both ascent and descent, the swing phase of the gait is the most troublesome. Having to support the body weight on one leg with a bent knee, with the pelvis tilting sideways and the other leg swinging forward, makes the probability of a fall when something goes wrong rather substantial.

Templer points out that people do not have enough time to regain their balance before an incident on a stair becomes a fall; our reactions normally come only after we have fallen about 180 mm and, since most steps have a smaller rise than that, there is not enough time for a controlled landing (and, of course, the surface for such a landing is probably a tread with a relatively small surface). People fall differently in ascent or descent, injuring different parts of the body, which can also depend on age. Older people are, moreover, more likely to receive fractures, while people under 20 years of age are more likely to injure their heads.

The book lists various historical specifications of step geometry, including Blondel's formula, and compares energy expenditure for stairs and ramps with different pitches. The conclusion is that higher rises with small goings are no more fatiguing than much lower rises with large goings—but the relation between human stride and rise-going geometry is less linear than Blondel envisaged. In addition to energy expenditure, Templer considers the effect of stair geometry on gait. In ascent, gait is less noticeably affected by stair geometry because much less of the foot needs to be placed on the tread (remember, no heels) but still, rises between 160 and 226 mm cause fewer missteps. Small rises result in more risers in a flight and, hence, more opportunities to trip. In descent, the steeper the stair and the smaller the going, the more missteps occur. Larger goings (292–360 mm) appear to be safer, while goings of less than 229 mm perform very poorly. Safe rises in descent are in the area of 117–183 mm. Going sizes are also linked to foot size; goings should be large enough to accommodate the length of the shod foot, especially in descent, where a larger part of the foot is used. Otherwise, users are forced to twist their feet sideways and adopt distorted gaits, moving arrhythmically in dangerous fashions. A going of 279–292 mm is proposed (good enough for 95% of the population). The compatibility between rises (maximum of 191 mm) and goings (minimum 229 mm) is summarized in a table that proposes that each acceptable rise is compatible with a range of goings, not a single one. For example, a going of 318 mm is matched to rises of 165, 152, and 140 mm, while a going of 343 mm is only matched to a rise of 140 mm.

Having considered stair geometry for the individual user, Templer moves on to the width of stairs for multiple users, primarily from the viewpoint of the individual user who has to adapt their speed, direction, and rhythm of locomotion to the presence of others. In the worst cases, congested places can go beyond distasteful or uncomfortable and become threatening. He points out that flight does not lead to a catastrophe unless inhibited or prevented and that congestion should never be treated as the normal state anywhere. Crowd disasters occur immediately after capacity has been exceeded, as crowds act on urgency, e.g., to escape danger but also to enter an entertainment venue.

The space required for locomotion on stairs is determined by (i) the body ellipse, minimally 710 × 480 mm, taking into account clothing and postural sway; (ii) pacing zones, 559 × 914 mm to allow a user to occupy two treads while moving from one to the other; (iii) the sensory zone, 1220 mm or four treads in ascent and 1830 mm or six treads in descent; and (iv), the buffer zone (for maintaining culturally and psychologically acceptable distances). If the buffer zone is violated due to, e.g., crowding, tensions arise, and behavior becomes defensive. Flow on stairs is analyzed in terms of speed, density, and space. Flow problems arise from route conflicts, reverse flow, overtaking constraints, and bulk arrivals that “force feed” stairs.

In terms of user behavior, Templer refuses to put the blame for accidents on users and illustrates that by the plight of people with just large feet “Gait on stairs is wholly dependent on placing our feet with accuracy on each step” (p. 113 [6]), meaning that goings should be no less than 280 mm or larger than 356 mm for a 127 mm riser. The smaller the going (and the larger the foot), the higher the probability of placing the foot wrongly. An even more critical tolerance relates the foot to the nosing; in both ascent and descent, the toe and heel must clear two nosings on the way to a new stance.

Handrails, guardrails, and balustrades are closely linked to the incidence and severity of stair accidents. Even if people do not use handrails, being able to grab them may abort or limit a fall. In descent, the hand preferably slides down the rail in a continuous motion, giving the user a sense of security and increased stability. In ascent, the hand grabs the rail at regular intervals, pulling the user up and increasing stability. The height of handrails depends on distance; the farther the user, the higher the handrail must be. An effective height for counterbalancing forces in descent falls (the most usual kind) is 910-1020 mm. A graspable shape (round for gripping), free from edges or projections (including adequate clearance from the wall), materials providing sufficient friction, tactility and resilience, and a design that reduces the force of an impact are recommended.

Guardrails can protect from falling over the edges of landings and stairs, so there is often a need for guardrails above handrails (at a minimum height of 1.07 m), even though handrails generally double as guardrails. Balustrades, on the other hand, may cause injury by trapping limbs or increasing the number of sharp and hard features during a slip or fall. A spacing not greater than 89 mm is recommended, as well as energy-absorbent materials and construction that can withstand the loads of a falling body. No height or other solution is prescribed for the acknowledged danger of children climbing onto the bottom rail of a balustrade. For the more infrequent sliding or rolling under the same rail, a toe board is recommended.

Finally, suggestions for avoiding the causes of falls and designing for injury reduction include (1) special attention to the top three and bottom three steps, which form critical zones; (2) focus of attention on stairs, not their surroundings, especially in the above critical zones and with respect to natural lighting; and (3) attention to nosings, which should be backward sloping rather than abrupt overhangs and no more than 175 mm in size. These are indicative of the care that should be taken for the whole environment of stairs, not only to each relevant feature individually but also to relations between features and to what users can and do.

### *2.4. After Templer*

The comprehensiveness and reliability of Templer's work are confirmed by many subsequent publications. Some have reiterated and experimentally substantiated his recommendations, for example, the significance of goings adequate for the shod feet of users, especially in descent [8,49–51], the problems that inconsistent rises cause [52], and the preference for tapered nosings [53]. Templer's flexible relation between rise and going is validated by research that demonstrates that step dimensions do not influence much older user behavior either in descent or in ascent [54].

Of particular interest is the use of optical illusions created by simple means, like highlighters. These help regulate user behavior (e.g., increase foot clearance without destabilizing posture [55,56]) and can, therefore, offset inconsistencies in rises, which is of particular practical value for existing stairs [57]. Similar highlighters are shown to be most effective as precise markers of goings when placed flush with the nosing [58].

## **3. Stair Safety**

### *3.1. Users*

Studies in other disciplines focus more on stair users and the biomechanics, kinematics, and kinetics of stair walking. Epidemiologic and ergonomic studies report that stair falls affect all users, with median ages reported at 35 years [10], and 67% of stair fall patients are 11–60 years of age [3]. Risky behavior is widespread, and 91% of young adults and 57% of older adults self-report being less than careful on stairs [59]. There is, however, general agreement that some categories are more vulnerable. In UK coroners' reports, 60% of total fall-related deaths were of infirm persons [7], while higher injury rates occur among children and older adults [3,10]. Females appear to be more at risk, and they represent 62% of stair fall patients in US emergency departments [3]. However, it is also reported that in the 0–75 years-of-age group, there are more male fall victims. Afterwards, females are the majority [7].

Adults over 60 may find stairs problematic due to age-related decline in physical capacity (changes in joint kinetics and the relative contribution of lower limb joint moments during stair ascent and descent), which becomes significant already after 50 [60,61]. To compensate, older adults (aged 77–89), especially those lacking confidence in their stair-walking abilities, tend to ascend or descend at a lower speed, use the handrails more, and stay close to the handrail [62]. In terms of movement, they use proportionally more muscle capacity to walk on stairs and they redistribute joint moments so as to maintain muscle output within comfortable limits [60].

The increased risk of stair falls in older adults forms a barrier to complete mobility both physically and psychologically, deterring them from using stairs [62–64]. Fear of falling relates to the deterioration of motor and perceptual systems, as well as to one's fall history. It reduces the degree of confidence in one's functional abilities and increases awareness of stair features for safe ascent and descent [65]. Routes that involve negotiating stairs may, therefore, be avoided, thereby increasing the exclusion and isolation of older people. Some may even avoid stairs altogether and so miss the physical exercise involved. In turn, they also lose part of their stair-walking skills in a vicious circle of inability, fear, and lack of confidence.

Older adults and children are not the only vulnerable categories on stairs. For people with larger feet, the small goings in many, especially private stairs, leave little margin for safety [5,64]. Lower rises and deeper goings are considered generally desirable, even more so for healthy older adults because these users perform closer to their maximum joint and muscle capacities on stairs [21]. It is suggested that increasing the minimum going in codes from 210 to 280 mm could result in an 80% reduction in fall risk [4]. With the growing numbers of older and taller people in most countries, this can be of particular value.

### *3.2. Ascent and Descent*

Epidemiologic and ergonomic studies also point out differences between ascent and descent on stairs. There is general agreement that most stair falls occur when people lose their balance on descent [66]. Descent is more demanding for all but especially older adults [60–62], who adopt different strategies, such as relying more on the trailing leg for limiting downward velocity and acceleration, as opposed to younger adults' reliance on the leading leg [67]. Regarding falls, there is a marked difference between, e.g., forward falls in descent, when balance recovery involves heavy use of handrails and compensatory stepping [68], and backward falls in descent, when users desperately try to clutch at anything that might arrest the fall, usually with limited success [51].

Ergonomic studies provide a detailed and coherent picture of user effectivities, including differences between age groups, as well as between ascent and descent. Of particular interest are data on stereotypical actions and general tolerances. For example, 90% of users stay at a distance of roughly 81 cm from the handrail during descent, keeping it at arm's length, and feet clear step nosings at slightly more than 1/5 in [66]. Similarly, the contributions of different parts to walking on stairs, from ankle and knee extensors to the hip [60], make clear the complexity of human movement on stairs and explain how sensitive different categories of users can be to either kinetic capacities or stair features.

In both ascent and descent, balance and postural control involve visual as well as vestibular and proprioceptive information (the latter being particularly useful for balance recovery). Balance recovery strategies can be either (a) fixed support, stiffening of leg muscles and beyond (including holding on to handrails) to control the movement of the body's center of mass, or (b) change in support, compensatory stepping so as to find a new base in support rather than reinforcing the previous one, which is, therefore, preferable, especially for larger balance disturbances and the more hazardous descent [12].

### *3.3. Prevention Strategies*

Prevention strategies that focus on behavioral issues [5] depart from the realization that stairs are inherently challenging because they require complex navigational actions [11]. Users may overestimate or underestimate the hazards involved and appear to hold differing views about safety on stairs [69]. Lack of confidence reduces stair use and even increases the risk of a fall, e.g., by making some people hold both handrails for safety in descent, even on stairs 1200 mm wide [45]. Just as a lack of confidence may reduce stair use, a high level of confidence may lead to unnecessary risks, as people shrug off minor incidents and largely neglect safety on stairs, especially at home [62,70]. For example, people often walk on familiar stairs with little or no lighting, although a lack of adequate lighting is a major cause of stair falls. This includes the bottom-of-flight illusion, when a descending person falls near the bottom of a flight because they mistakenly perceive the last tread for the landing [13].

Allowing to be distracted by another activity is also an indication of overconfidence or disregard of risk. Multitasking while walking on stairs is a major factor in stair falls [3]. Even cognitive tasks, like mental subtraction with three-digit numbers, while walking on stairs can be so demanding that they cause 67-year-old women to decrease gait speed, foot clearance, and hip flex extension and increase step width in order to enhance body stability [61]. Other behavioral aspects that play a role include substance abuse. In 60% of all fatal falls in UK coroners' reports in the under-50 age group, alcohol was involved [7]. Finally, failure to keep stairs and their direct proximity free from clutter and trip hazards increases the risk of falls. Even movable furniture near stairs has been reported as a cause of stair fall [3,7]. Nevertheless, in one study, 70% of 253 residences used at least one stair for temporary storage [70].

Recommendations for personal measures in stair use for healthy young adults include [21] the following:

- Restriction in the use of high-heeled shoes;
- Limits to carrying heavy loads;
- Treatment of limb injuries and visual impairments that affect safe stair use.

For healthy older adults, continuous handrail use is, furthermore, highly recommended. For people with health conditions, more research is necessary [21].

Regardless of the faults of users and also because human error is difficult to control and ultimately inevitable [8], as well as because stairs are inherently more dangerous than other environments [21], epidemiologic and ergonomic studies generally prioritize improvements to the environment order to prevent or reduce stair-related injuries [3–5,11,13,63,71]. Measures proposed concern maintenance, which is considered relatively easy to achieve, and design of stairs, which should go beyond the obvious aspects present in regulations [8,12,21]. They include the following:

- Adequate ambient lighting, so that steps and landings are visible and distinguishable;
- High-contrast visual cues of step edges for the same reason;
- Sturdy, reachable, and graspable handrails at the right height, continuous and extending beyond the flights in order to provide physical and psychological support and guidance to users;
- Cues that focus attention on handrails;
- Goings large enough to provide adequate footing;
- Stairs that are not too steep, i.e., lower rises;
- Stair widths that take into account postural sway, as well as the presence of others on stairs;
- No dimensional inconsistencies, so that steps in a flight are uniform (of particular importance for safe descent);
- No sloping steps.

These measures should also be applied to the existing building stock, but this is rather hard to achieve [3,5]. Consequently, most studies focus on the improvement of stair standards in building codes and design regulation as a means of narrowing the gap between generally applicable minima and the needs of users [3,5,11,63]. The improvements generally focus on stair dimensions, but some also consider clarity, e.g., removing confusion between related components, such as guardings and handrails [13].

In conclusion, epidemiologic studies have been criticized for being uninformative on features of the stairs and user interactions [63], lacking both detailed and structured assessments of environmental features and standardized psychometric measures for the users [11,71]. Nevertheless, they manage to convey clear indications of the urgency of stair-related injuries. They also position them in the context of wider human activities, including ones that are facilitated by the ability to walk on stairs and others that may distract us from taking due care. Ergonomic and safety studies have also been criticized for their scope, in particular their small samples and relative lack of investigation of the relations between stair features and the risk of falls [71]. Even with such limitations, however, all these studies are consistent with and complement architectural knowledge by providing a better understanding of the contributions of various stair features and compelling reasons for paying attention to all of them. They also transparently link stair walking and environmental specifications of stairs to their context: the activities and effectivities of users.

### 3.4. Domain Knowledge Summary

What designers should know about stairs is admittedly a lot, but this is fitting for such a complex and hazardous environment. Stair design and innovation are primarily motivated by considerations other than functionality, so it is easy to prioritize spatial, aesthetic, or structural issues and underplay comfort or even safety, especially if the latter are imposed as irritatingly long and meaningless lists of constraints. Learning the dangers associated with each feature from ergonomic, epidemiologic, and other studies helps designers understand their significance but even then, the lists of constraints do not become any shorter. Moreover, explanations of this significance may become segregated in silos and impede creative explorations that feed on rejected solutions [72,73] by failing to provide coherent and comprehensive overall criteria for design analysis and evaluation. Indeed, judging from the current state of stair design [74], truly innovative designs are sorely needed. To improve the situation, we need to step up our game and provide a more comprehensive and coherent account of how users interact with stairs.

## 4. Stair Affordances

The promise of affordances lies in that they (a) frame actions and interactions in the whole of an environment [75]; (b) connect probable actions and interactions to the effectivities of a specific user; and (c) link action to perception in a direct and automatic manner. The last was the starting point in a sequence of important stair-related affordance studies.

### *4.1. Warren's Foundation*

Gibson was insistent that affordances are relative to species and individuals, generally commensurate with their own body; an animal perceives the size of a drop off and the actions it affords relative to its own size [26]. Warren's paper on affordance perception, using stair climbability as the exemplar case [40], is celebrated for succeeding in quantifying this and finding a precise description of animal–environment fit for stair climbing. An important reason for choosing this particular environment is that stride length and lift work for each step on stairs and are prescribed by stair properties, so an optimal gait cannot be freely adopted. Such a close fit suggests possibilities for clearer identification of what really matters.

Warren's paper focuses on the relation between energy expenditure and visual perception; the perceptual category boundary between climbable and unclimbable stairs. Its goal is to find a body-scaled metric for this boundary in visual information, as opposed to extrinsic or absolute measures. The paper is critical of existing stair calculations. Blondel's ubiquitous formula is criticized for having a dubious biomechanic basis and resulting in rise and going combinations that are not always appropriate for the effectivities of the stair users. The paper stresses that in addition to geometric variables, there are also kinetic ones. The elasticity of a walking surface, for example, affects energy expenditure and the top running speed of an animal. Among geometric stair variables, the pitch is underplayed. Instead, the stair diagonal is proposed as having a direct relevance to the stride length of the climbing gait. On the user side, the paper is restricted to two dimensional ratios: R/L (riser/leg length) and D/L (diagonal/leg length).

The paper considers visual guidance of stair climbing and the perceiver's capability to detect both the limits on action and the most efficient paths of action. Its particular foci are the critical points (phase transitions) and the optimal points (stable, preferred regions of minimum energy expenditure—the "best-fit" affordances) in stair climbing. The critical point on stairs is deemed the transition from bipedal to quadrupedal climbing. For the critical point test, rises of 50.8 to 101.6 cm (20 to 40 in in steps of 5 in) were visually evaluated for climbability by a group of tall and a group of short people, using a scale of 1 to 7 (least to most sure). The result of this first experiment was that for both groups the climbability boundary was an R/L ratio of 0.88 (critical pi value).

The optimal rise was measured by oxygen consumption on an adjustable motor-driven treadmill. The rationale behind this second experiment was that (a) as rises become lower, more step cycles are required for a given distance, leading to an increase in total muscle activity and energy expenditure, and (b) as rises become higher, higher effort due to the higher flexion at the knee and hip increases energy expenditure. The combination of these two factors should determine the rise that minimizes energy expenditure. The results were a 19.61 cm rise for the short group and a 24.18 cm rise for the tall group, an R/L of 0.26. Consequently, the paper argues for higher rises and shallower goings on the basis of ergonomic factors and recommends rises of approximately 17.8 cm and diagonals of 35.6 cm (i.e., goings of 30.8 cm).

The third experiment examined the visual perception of the optimal rise determined in the previous experiment. Asked to rate the effort required for rises of 12.7 to 25.4 cm, tall and short subjects chose heights that amounted to an R/L of 0.25—very close to the energetic optimum of 0.26. This suggests the existence of intrinsic optical information specific to the path of least work; perceivers can see the best energetic fit with the environment for a particular activity. This probably comes from a complex of ecological relations, indexed in earlier activities, including exploratory ones. Perception is, therefore, anchored in the biomechanics and energetics of action, which provide a natural basis for categorical distinctions and preferences.

### *4.2. Body Scaled and Action Scaled*

Warren's paper established that perception of affordances is based on intrinsic measures, related to an animal's effectivities. Perception of affordances was also shown to mean judgment of critical action boundaries. Further research continued on these themes, trying to establish the right intrinsic scalar, e.g., eye height rather than leg length [76]. Subjects other than Warren's young adults were also considered. Six-, eight-, and ten-year-old children have the same leg geometry as adults and were found to have the same 0.88 R/L stepping boundary [77]. This was confirmed for persons between 5 and 21 years of age [78]. Older adults, on the other hand, had divergent boundaries; tall ones were at 0.73 R/L and shorter ones were at 0.62, instead of, respectively, 0.89 and 0.91, as predicted by Warren [79]. Later research also measured lowered ratios among 53–72-year-old adults [78]. Such differences between age groups suggested that affordances may not be just body scaled. A study of young females with varying degrees of hip joint flexibility and relative leg strength identified significant differences in perceived action boundaries in terms of R/L ratios [80].

The call for additional functional criteria (kinetic or kinematic) was expanded with studies that compared young and older adults [79]. In these studies, it became obvious that leg length was not the only limiting factor. Climbers had to also generate enough vertical force to lift one foot to the next step and enough torque around the knee to move the center of body mass over the new base of support. The quadriceps, knee flexors, and flexibility at the hip joint were among the factors that were seen to play a role. It was, therefore, suggested that the intrinsic scalars of affordances are not just body metrics but include additional locomotor capabilities, which vary during a lifetime—not just due to age but also because of fatigue, injury, or activities, such as carrying a heavy load [81]. For step and stair climbing, the following were proposed [79], matching effectivities to gait phases as follows:

- Leg length;
- Leg strength and hip flexibility (for placing a foot on a tread);
- Leg strength (for pulling up the body over the new base of support).

A study on the perception of stair steepness used a realistic stair as a test case, including 39 steps bridging a height of 6.45 m, with a total pitch of 23.4% (including half-landings) and a flight pitch of 28% [82]. Women and older, heavier, and shorter people (typically preferring escalators or lifts) reported the steepness of stairs as higher than comparison groups. This perceived steepness, therefore, acted as a cue for avoiding using stairs. The exaggeration was purely verbal and visual; haptic perception through a palm-board did not exaggerate. Establishing a relation between stair pitch and animal weight is interesting and useful, considering that the total body weight comprises dead weight, including fat, which must be carried, and muscle, which has to do the carrying—two related variables with opposing effects. Moreover, pedestrians carrying heavy loads also preferred escalators [82].

Studies also confirmed that people are quite good at perceiving affordances; despite boundary differences, all age and size groups perceived boundary values remarkably close to their actual action boundaries. Older adults had a higher and more precise match, presumably because they operate within smaller ranges of action capabilities, which makes them more sensitive to even small environmental changes [79]. This was also supported by analyses of demanding actions, e.g., in sports, which show that people are remarkably flexible in adapting to task constraints and their changes, such as the direction, height, and speed of a ball in relation to the position and disposition of opponents. Such perceptual attunement to different variables in the information that surrounds an animal allows it to adapt its behavior to emerging affordances in advance [83].

Other researchers suggested that affordances for both children and adults are not directly related to limb geometry but rely instead on the effectiveness and reliability of motor performance. By choosing other criteria for climbing affordances, such as foot clearance and the resulting safety margin, and applying them to rises below the critical limit, they detected differences in the behavior of children and adults; children had higher levels of variability and the highest clearances, while adults had lower levels of variability and lower clearances [84].

Compromise positions stressed the insufficiency of body-scaled affordance perception under several conditions, such as when objects hang in the air, when surfaces are tiered or sloping, and when the dynamics of the body are needed (e.g., when moving through apertures or around obstacles). Locomotion, in general, was seen to require affordance perception that extends beyond the selection of an action or boundary to the continuous control of body movement in ways that take into account the environment, the animal's own body dimensions, and its locomotor capabilities. In fact, the dynamics of movement provided affordance yardsticks, e.g., lateral head sway as a scalar for the size of an aperture and stride length to all kinds of walkability and climbability. An animal is capable of calibrating and recalibrating the mapping between relevant units in perception and action if the characteristics of the environment or the animal itself change. The same applies to changes in the relation between action and body dimensions, e.g., head sway amplitude and body width [81,83].

More recently, the distinction between body-scaled and action-scaled scalars has been dismissed as largely artificial [85,86] or even misleading and possibly entirely fictitious—a reification of a priori hypotheses [87]. Some behaviors are seen as primarily constrained by static (geometric) properties of the animal, e.g., vertical reaching while standing. Others are additionally constrained by dynamic capabilities, such as muscle strength and joint flexibility, e.g., vertical reaching while jumping [86–88]. Even how an action is performed can change motor capabilities, such as the arm swing in the long jump [85].

The static properties of the body, e.g., length or weight, are seen as exerting influence over action capabilities through their impact on body movement. Reversely, affordances formalized in geometric terms are constrained by non-geometric, dynamic properties, which include strength, flexibility, coordination, and balance [86,87]. Some researchers even consider static properties to be dynamic and the only ones that change over much longer time scales, making the perception of body-scaled affordances a special case of action-scaled ones [86]. Others distinguish between the kind of actions involved, e.g., non-launching ones and, hence, less constrained by dynamic capabilities, or launching ones, such as stepping across an expanse versus leaping across it [85,86]. Perception of affordances in launching actions, even familiar ones, tends to be grossly underestimated because launching actions are inherently more variable and involve more factors [85]. One could, therefore, suggest that using body-scaled measures amounts to a cognitive economy that allows us to ignore demanding and complex dynamic factors in situations where they have a limited effect.

The argument for the economy is indirectly supported by the lack of action-scaled measures; while the complexity and interdependence of factors in action are convincingly presented, no measure with the simplicity of R/L has been proposed for stairs, with only one exception: the angle defined by the rise and the position of the trailing (support) foot before it. This angle appears to be the same for children and young and old adults, despite differences in motion kinematics, anthropometrics, or climber skills. In fact, it is supported by the similarity in the kinematics of the ankle trajectory and maximum closure of the joint [78], which directly relate to a critical part of the stepping action.

Finally, one should avoid limiting expectations concerning effectivities to stereotypical actions; 18-month-old infants, who are already experienced walkers, refuse to walk over risky drop offs, choosing instead alternative methods, such as crawling. Animals use a wide range of skills and strategies, and affordances and their perception appear to relate to the specific action; infants' motor decisions become more accurate over weeks of crawling experience, but learning starts all over again when they begin to walk [88]. They do not acquire generalized responses, like a fear of heights, but learn to perceive affordances for the experienced action.

### 4.3. Beyond Steps

The debate on body-scaled and action-scaled measures of stair affordances has advanced our understanding of user effectivities and our knowledge of human–stair interaction, in particular concerning the boundaries of a single step, following Warren's first experiment [76,78–80,85,86]. Boundary perception is foundational, but stepping over or onto something is not the same as locomotion on stairs. Moreover, stairs are an extreme example of the reciprocity between animal and environment; in an environment ostensibly designed to meet the ergonomic needs of its users, the animal's behavior is severely constrained, resulting in a gait regulated by the stair geometry. This makes affordance perception through systems other than the visual more important; the motor system informs on the sequence and consistency of the stairs, often making it easier to ascend or descend without much visual attention to where and how the feet meet the treads. Reversely, any irregularity, including the minute rise differences that may lead to a trip and fall, is first perceived by the motor system, as pointed out by Gibson [27].

The action-based approach is a reminder that people do all kinds of things on stairs, from walking and crawling to carrying objects and sitting on steps. They also run on stairs, which may be radically different from walking in terms of affordances and related judgments [85]. Furthermore, as AIT explains, what people do on stairs usually serves other activities and objectives, which have to be taken into account in the behavior of stair users. A comparison to affordance perception in sports can be helpful in this respect; actions in sports are highly demanding, generally fast, and often subtle. They are goal driven, severely constrained by the environment (including equipment and regulations), and must be carefully planned and executed to be successful. Despite all that, athletes typically manage to perceive the affordances of the situation and manage their tasks with relative ease and grace [83]. The same holds for many real-life situations (as opposed to laboratory experiments on climbing a single big step), e.g., walking on the stairs of a crowded station under time pressure to catch a train, although not always involving the same small error margins as in sport. If affordances can add functional semantics to sport [83,89], they can certainly also help with the complexity of actions on stairs, where error margins are quite small and users are generally remarkably capable, not unlike trained athletes.

In considering real-life complexity, affordances have the advantage of going beyond competence (most people can walk on stairs) to cover fluency; if one perceives that they are able to do something without conscious attention to it or hesitation or conflict with other actions in the same activity, then the action is performed fluently as a Type 1 process [90,91], achieving the regular gait needed for efficient and safe walking on stairs.

### 4.4. Physical, Social, and Cultural Affordances

In addition to what physical environments afford to an animal (physical affordances), other animals have affordances, too; for example, nurturing from a parent or mating with another animal [27]. Social affordances can be categorized into [83] the following:

1. Affordances of another animal: what they can do in a given context, e.g., whether and how another person using the same stair can break their fall;

2. Affordances for joint action: what the perceiver and others can do together, e.g., carry something on a stair;
3. Affordances of another animal: what another animal affords the perceiver in a given context, such as when an adult walks hand in hand with a child for guidance and support on a stair.

Closely related to the first category is learning what an environment affords by perceiving what others do in the same environment. Observing how others match their effectivities (which the perceiver may share to a large degree) to a common environment is a fundamental way of learning what the environment affords to the perceiver. It also helps us anticipate the future actions of others, judge their ability to perform certain actions, and plan our own or joint actions accordingly, e.g., avoid a falling person on the stairs or help them stop their fall. Social affordances are present in the kinematics of actions, as evidenced by how the control of motor sequences changes by social interaction [92–94]; for example, when a request gesture, like the opening of a mouth, increases accuracy in feeding another person [95]. Similarly, when walking with small children on stairs, accompanying adults adjust their own movement and the guidance afforded to the child by the child's progress and expressions of difficulty.

Affordances can also be cultural; a cordoned-off stair no longer affords ascent or descent (Figure 1). In the case of a piece of rope, cultural affordances draw from physical ones to prohibit or direct, but cultural affordances can be highly abstract, such as the foam lines that position the ball and the wall in soccer free kicks or lines in the pavement that indicate where bicycles may be parked in Dutch cities (Figure 2). Traffic lights and signs similarly create cultural affordances not for themselves but for the wider environment (the roads and traffic in their proximity). Finally, cultural affordances may be also part of the behavior of the perceiver and other animals, such as the observance of conventions; for example, walking on the right side of stairs (regardless of the side where the handrails are).

**Figure 1.** Cultural affordance: a cordoned-off stair is not climbable.

**Figure 2.** Cultural affordance: bicycle parking constrained by lines on the pavement.

Physical, social, and cultural affordances together define an environmental triangle within which actions occur, drawing from all three sides [83,92]. Some affordance researchers treat physical affordances as generic and social ones as products. For example, a flat, relatively smooth surface affords soccer playing; not just something with a ball on that surface but a team activity with intense social interactions [96,97]. In their view, social and cultural aspects form a context that restricts the utilization and shaping of affordances [98]. However, social affordances may be leading; a group of children wanting to play soccer together may choose to do that on surfaces that are far from flat or level. They may even do it on stepped surfaces and develop cultural affordances that compensate for negative physical affordances, e.g., rules for defending downhill or the ball bouncing against partly bounding walls and obstacles in the middle of their "soccer pitch" [99]. In short, the perception of affordances, even though direct, is not unmediated by how one acts and what one wants to achieve. In AIT terms, the social and cultural purpose of an activity helps understand its meaning and frames the perception of affordances, providing constraints that bind actions and operations [100,101]. A striking example of how direct this can be is the curious appearance of Western chairs in Japanese home interiors, as captured in Yasujirō Ozu's early post-WW2 films. The low-angle camera position ("tatami mat shot") corresponds to the eyer height of a person sitting on the tatami floor [102], as was customary at the time, and renders the Western chair seat too high to be sittable. Indeed, chairs appear more decorative than functional and are generally left unoccupied in Ozu's films.

From a design perspective, the environmental triangle of physical–social–cultural affordances is a strong reminder of the multidimensionality of design problems, which must take into account a multiplicity of users and activities in an inclusive and performance-directed manner. Thinking of users and activities in terms of affordances rather than required floor area sizes and ergonomic dimensions is a key enabler because the behavior of users is not abstract but situated; it is different on stairs than in, e.g., corridors, but also similar (based on fundamental effectivities and perceptual capacities). It is, moreover, different on different stairs. These differences are meaningful to users because they reflect possibilities for action in relation to their effectivities and probabilities of actualizing these in the context of their activities, both of which should be part of the design brief.

## 5. Discussion

The state of the art in stair design is regrettably and depressingly familiar; there is enough knowledge available in the architectural domain and other disciplines, but it fails to be utilized. More than campaigns aimed at users, it is architects' compliance with norms and regulations that should concern us; out of 578 stairways, the images of which were published in a leading architectural journal, 61% had at least one visible design hazard. Among these images, 78 (13.5%) were in product advertisements. Of these, nearly half (47%) exhibited clear hazards [74]. This goes beyond ignorance or neglect; architects take pride in showcasing hazardous stair designs, such as ungraspable glass guardings without handrails [103] or discontinuous handrails [104], which surely contravene the recommendations of any textbook or code.

The obvious direct solution is to make the available knowledge easily and comprehensively accessible to designers. For example, the collection of recommendations summarized in the present paper can be turned into a checklist for evaluating stair designs point by point. It should not matter whether the required features and constraints are present in existing regulations. Stair regulations in many countries are in urgent need of improvement that go much further than finally rejecting Blondel's formula and its variations. As a study of walkway codes suggests, there is still considerable room for focused scientific research into, e.g., user adaptability, handrail height, graspability, the assumption that users adapt to steeper stairs at home, etc.; it may even be necessary to ban short stair flights on grounds of documented hazards to pedestrians [105].

Legal constraints are minimal or rarely enforced, so professional knowledge and responsibility should be leading. Accountability is also a good motivation for designers, as well as owners and operators of buildings, for properly designed, constructed, and maintained stairs, including under extreme circumstances, such as fire egress [12]. The inevitable increase in cost and loss of floor space is easily offset by the costs of user injury or death [8]. Stair safety should, consequently, develop into a key selling point of a design rather than an imposition so as to promote creative, innovative, and empathic solutions that supersede existing regulations and precede better future ones. Riding on the wave of health can be significant; propagating stair use for health reasons presupposes that stairs are made safer and more attractive to all users.

In both regulation and design, one must take into account demographic changes and their effects, such as the increase in older users and their different strategies of safe stair walking [67] or the larger feet of younger generations [8]—developments are not often or fast enough taken into account when updating building codes. One also has to abandon old, normative concepts, such as walklines. It is not sufficient that only a very small part of the treads has adequate goings; there should be enough width for postural sway in private residences and for multiple users in public buildings.

In addition to what is evaluated, one must pay attention to how compliance is tested [105]. A comprehensive checklist is a low-threshold solution for verification [106], but the dynamic and variable character of user interaction with stairs suggests that validation requires coherent, holistic views of user behavior and interaction, which can also provide guidance. Stairs will inevitably remain complex environments, full of possibilities and dangers and often made even more complex by design limitations, such as a reduction in the floor space they occupy or the omission of landings. Simplistic solutions that reduce stair functionality and safety to step dimensions and the presence of handrails are clearly insufficient. Stair walking, similar to many interactions with the built environment, will always remain in the realm of Type 1 processes and, in the AIT classification, at the level of operations; a collection of small tasks we execute automatically. Users can be trained to take safety measures, such as avoiding carrying too much or turning on the light on stairs, but even the most careful of users is in danger on a poorly designed stair, e.g., with insufficient goings and irregular rises.

As with most analytical descriptions of common Type 1 actions, one is amazed by the fine balance between human vulnerability, unconscious fine coordination and control, and interaction with the environment and other beings. It seems remarkable that there are not many more injuries with the things we do, given the limited attention we consciously pay to various dangers. It also suggests that we learn to control our interactions, compensate or reinforce their effects, and adapt to environmental or effectivities changes, such as the shift in using handrails from crutches in childhood to safety nets in youth and again to crutches in old age, infirmity, or other demanding situations [6]. We appear to develop numerous Type 1 processes that are attuned to the nuances of the world, through which we utilize or amplify our capacities in positive affordances while neutralizing danger and reducing negative affordances. This happens in a very direct and economical manner;

locomotion is guided by the perception of walkable surfaces, as well as barriers, obstacles, and other features with negative affordances. Steering away from these is usually specified in very simple ways; the imminence of collision, for example, is clear by the explosive rate of magnification in the optical field [26]. Equally remarkable is that we put such processes together in larger chunks in Type 1, as AIT explains, in the service of higher objectives for which Type 2 thinking is needed. Achieving a regular, unimpeded, and unhurried pattern of locomotion that makes stair walking safe and efficient is among them.

Stair designers should not be lulled into complacency by the impressive tolerances and adaptability of users and ignore the fine margins of error that may lead to considerable costs due to predictable injury. The same holds for the cognitive effort of negotiating a poor stair, which surely distracts from the architectural intent behind the stair and its relation to the rest of the building. Instead, designers should be taught to approach stairs from the viewpoint of affordances and integrate the long checklists of stair features and constraints into succinct yet multivariate descriptions of user behavior and interaction. An important reason for that is that affordances are not binary (possible/impossible) but graded; users adapt their behavior to overcome limitations in the environment; for example, turning sideways in narrow passages [107] or treading more carefully and grasping the handrails on slippery steps. Consequently, rather than looking for critical thresholds that arguably describe extremes of performance rather than what people can do consistently, designers should consider affordances as probabilistic functions that represent an individual's likelihood of successful performance [108].

The educational purpose of affordances is to help designers understand interaction with stairs in terms of the full range of possible user capacities, actions, and interactions rather than a small selection of sizes and features. The climbability of a stair changes if one happens to have a knee injury, carry something uncomfortably large, or have a small child in tow. In each case, there are different effectivities and stair features that matter. And, although affordances are individual, it is easy to identify common characteristics and patterns. Future research could supply design practice with precise typologies of stair users and actions, but even without them, designer intuition and empathy suffice for mentally mapping the whole activities of multiple users onto stairs. This mental simulation is similar to, e.g., how visitor flows are mapped through an exhibition hall, taking into account not only pedestrian movement but also the viewing of exhibits and possibly interactions that increase user appreciation of the building. The evaluation of stairs can, therefore, be based on the following:

- Mapping activities on a stair and comparing the expected affordances to what the stair actually presents;
- Looking out for perception of negative affordances, which leads to feelings of insecurity and uncertainty;
- Investigating limitations to the perception of affordances.

The last point is of particular importance because stair design should nudge users to safe behavior [109], including a regular gait (which is often hard to achieve on narrow helical stairs) or holding handrails (which depends on the form of the handrail). Nudging is not the same as presenting users with a supposedly safe environment to which they have to adapt—a design attitude that has led to many prominent and persistent failures in architecture [110]. It involves using suitable defaults (e.g., opting out of organ donation instead of opting in or automatically turning the lights on in a stairway rather than expecting the user to turn them on) and making the available options and their effects comprehensible in both short and long term so as to prevent people from taking simplistic solutions when the number of choices and complexity of problems increase. The case of the automatic Type 1 interactions with an environment generally amounts to presenting users with the right affordances and making certain that they are clear to all; if the action possibilities are there, it is highly probable that most users will perceive and act on them.

With regard to that, affordance research needs to make clear what really works in terms of gradedness; instead of looking for critical thresholds that arguably describe extremes of performance rather than what people can do consistently, researchers should treat affordances as probabilistic functions that represent an individual's likelihood of successful performance [108]. There is a clear necessity for multidisciplinary research that

- Updates existing architectural knowledge: the features, constraints, and effectivities identified by Templer and others need constant revising to address new demographic and cultural developments, from population aging to smartphone usage, and link these to hazards on stairs and their causes.
- Explains how different perceptual and motor systems work together to present stair affordances. Many critical interactions are already known, but relations between them, e.g., step climbability and handrail graspability, visual perception of step edges, and all other ways that local interactions compensate or reinforce each other must develop into fully integrated descriptions of stair affordances. Social affordances are a clear priority in this respect. In other words, research has to develop holistic, descriptive measures of interactions in real environments.
- Develops efficient simulations of stair interactions: in the long term, designers need to rely less on their intuitive capacities and more on computational means, such as simulations of stair ascent and descent by various virtual users, in which all aspects and their interrelations are included, on the basis of the above descriptions and measures.
- Move from reduction to realism: single factors and laboratory experiments with limited stair types, artificial conditions, and high costs should give way to real environments and holistic measures of interaction. New technologies can play an important role in this respect [21]; for example, shoe sensors that measure foot placement and clearance on steps [111]. Studies using such technologies have indicated that laboratory results are different from those obtained in laboratories [23]. Data-driven technologies [112] can make transparent all the relevant features, effectivities, and relations that determine "stair climbability" and acknowledging the many small skills required of a competent and fluent user [113] so as to finally cover in full the wealth of domain knowledge.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The author declares no conflicts of interest.

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