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THE ROLE OF SPATIAL REFERENCE FRAMES IN ARCHITECTURE
Misalignment Impairs Way-Finding Performance

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ABSTRACT: It is generally recognized that the spatial structure of a building is an important factor in way-finding performance. However, surprisingly little research has related way-finding performance directly to topological and geometrical properties of spatial environments. In this study, the authors provide empirical evidence that way-finding performance and the ability of people to orient themselves in their environment depends partly on geometrical relations between different parts of the space. The authors propose that the misalignment of local, cognitive reference frames suggested by architectural features leads to way-finding problems and impairs the integration of spatial knowledge. In an experiment with 56 participants, the authors tested way-finding performance and spatial memory for four virtual environments. Environments differed systematically in their alignment of parts of the building. Results show a main effect of alignment for both way-finding and pointing measures. Implications of these findings for both architectural design and cognitively motivated formal models of space are discussed.

Keywords: spatial cognition; spatial memory; way finding; architecture

Architectural design of space has multiple functions, differing widely from one project to the next. Architecture can try to satisfy functional,
representational, aesthetic, or emotional needs of organizations or the people who live, work, or otherwise navigate in these structures. This article emphasizes one particular functional aspect of architectural design: human way finding (see Carpman & Grant, 2002, for an overview). When focusing on the usability of human-built structures, issues of finding one’s way and having a sense of where one is located can be seen as one of the most important functions (Arthur & Passini, 1992; Passini, 1984). Other functional or ergonomic characteristics, like workplace design, climate, and lighting conditions, also play an important role in the usability of built spaces but will not be discussed here.

When focusing on way finding in large-scale built environments, the spatial layout and other architectural features are an important source of information for finding one’s way. From a perspective of function, a building can thus be considered a design success if it allows easy and error-free navigation. This view is also adopted by Passini (1984), who states that “although the architecture and the spatial configuration of a building generate the way-finding problems people have to solve, they are also a way-finding support system in that they contain the information necessary to solve the problem” (p. 110). The view of the building as a source of way-finding information has led to the coining of the term architectural legibility as an indicator for way-finding performance (O’Neill, 1991; Weisman, 1981). Any attempt to increase way-finding performance therefore implies matching the particular cognitive, perceptual, and motor abilities of users with the appropriate architectural design to reduce the complexity of the way-finding problems.

Two main areas of research can be distinguished that have dealt directly with issues of way finding in architectural spaces. First, researchers have investigated the link between floor-plan layout and user’s performance in navigating the corresponding space (O’Neill, 1991; Passini, 1984; Peponis, Zimring, & Choi, 1990; Weisman, 1981). For example, a high positive correlation is usually found between the perceived figural complexity of a floor plan and the difficulties in navigating the space (Weisman, 1981). Second, research has focused on how the appearance of architectural features, like

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hallways, entries, or atriums, in addition to appropriate signage can assist and guide users in their way-finding task (e.g., Arthur & Passini, 1992).

In the following, we will present some of the research that predicts way-finding performance based on spatial properties of built space, especially analyses of floor plans. We will then report recent findings from studies of spatial cognition, which provide additional insights into the ways humans organize and access spatial knowledge relevant for way finding. Building on theories of the organization of spatial memory, we will propose a new perspective on a particular aspect of architectural legibility and a prediction of way-finding performance in this context. An empirical study, using four synthetic, computer-generated office-building environments, will demonstrate that the predictions derived from basic research have real and important implications for way-finding behavior and thus for architectural design. Both the practical application and the benefits of our research methodology will be discussed in the last section.

ARCHITECTURAL LEGIBILITY AND FLOOR-PLAN ANALYSIS

Even though Lynch (1960) identified the important role of the physical environment for spatial legibility and for way-finding issues early on, surprisingly few research projects have tried to predict way-finding performance from a systematic analysis of topological and of geometrical properties of the information available in floor plans (Peponis et al., 1990). A potential goal of this line of research is providing an objective, quantitative approach to validly predicting way-finding performance during the early planning stages of a building. One level of analysis deals with the topological complexity of a floor plan as a predictor for the difficulty or ease of way finding within a building (O’Neill, 1991; Passini, 1984; Weisman, 1981). O’Neill (1991), for example, presented an analytical measure of complexity in the form of his interconnection density index (ICD). In general terms, the ICD index reflects the average number of connected decision points for each decision point in a particular environment. The general usefulness of this measure has received empirical support; significant correlations between the ICD index and actual way-finding performance have been found (higher ICD-complexity of a floor plan correlated with more way-finding problems as measured empirically). Similarly, Weisman (1981) has reported positive correlations between judged figural complexity and problems in way finding.

Although these approaches certainly are valuable as a general tool to identify complexity related way-finding problems, the relation between topological measures, such as the ICD, and way-finding performance falls apart when
the analysis is limited to floor plans with similar ICD values or to floor plans
that differ in geometrical but not in topological descriptions (e.g., orthogonal
vs. nonorthogonal layouts or curved hallways). Figure 1 provides some
examples that illustrate this point. Comparing a straight hallway with a spi-
raling hallway (Figure 1b), the ICD index assigns both a value of 1, which
intuitively makes a lot of sense because in both situations, one can only walk
in one direction from each endpoint until one reaches one’s goal. Evidently,
however, the graphical complexity of the two floor plans (either measured
empirically through rater judgments or in terms of other complexity theories,
such as the SIT-index by Leeuwenberg, 1971) is different. This shows that
perceived figural complexity and way-finding problems can be dissociated,
and therefore, judgments of figural complexity cannot always accurately
predict way-finding performance.

More importantly, these and other analytical approaches, like space syn-
tax (Hillier, 1996), do not differentiate between the floor plan as a figural
entity and its perception as a large-scale space that can only be perceived
sequentially. In contrast, as Le Corbusier (1986) pointed out more than 70
years ago, the perceivable geometrical, two-dimensional depiction of a spa-
tial environment can differ dramatically from the experienced structure of a
spatial environment (p. 187). Figures 1c and 1d illustrate this point. Both
depict similar floor plans of an office building; the first depicts a square hall
that other hallways emanate from in an orthogonal fashion, and the second
depicts a diamond-shaped hall with a similar hallway structure radiating
from it. This description matches most observers’ descriptions of the floor
plans. However, if a person were to find themselves in a hallway or a circula-
tion system at the center of the floor plans depicted in Figure 1c and 1d, they
would perceive themselves at the center of a square hall. In the case of Figure
1d, the system of hallways is now oriented at a 45° angle, with respect to the
orientation of the square hall. The perception of the hall as a diamond-shaped
figure has been substituted for the perception of the space as a square, in
effect, rotating the spatial frame of reference used to describe the floor-plan
layout. Although topological descriptions are insensitive to these differ-
ences, recent efforts to apply formal geometrical analyses to spatial layout
might start to differentiate these situations (Peponis & Wineman, 2002;
Peponis, Wineman, Rashid, Bafna, & Kim, 1998). To our knowledge, how-
ever, even these formal geometrical descriptions of space do not acknowl-
edge differences in orientation of space or in orientation of shapes. Recent
findings in spatial-cognition research suggest, however, that the two situa-
tions described above are processed quite differently by the cognitive system.
The determined orientation of salient axes within an environment, and the
designated frame of reference based on these axes in particular, have been
shown to have large effects on the availability of spatial information in a wide variety of tasks. In the next section, we will outline how the assignment of local reference frames might impact a user’s ability to navigate an environment successfully.

THE ORGANIZATION OF SPATIAL MEMORY, MISALIGNED REFERENCE FRAMES, AND THE IMPLICATIONS FOR WAY-FINDING TASKS

One of the first steps in the interpretation of visual form consists of the assignment of a common frame of reference to relate different parts of a figure to the whole (Rock, 1973). There are multiple, sometimes competing solutions to the problem of which reference frame to assign to a figure. Features such as the axis of symmetry, elongation, functional characteristics, or the viewpoint of the observer might provide a basis to select and anchor a reference frame for a particular figure or scene. For large-scale environments like an office building, this basic problem is exacerbated. Spatial information about the relations between different elements of one place or between different parts of the building has to be integrated in terms of one or multiple frames of reference. In the case described above (see Figures 1c and 1d), observers of the floor plans have a constant frame of reference available, namely, the orientation of the paper or the plan itself. This reference frame leads to the description of the center of the hall as a diamond with respect to the orientation of the plan or page. When actually experiencing the spatial environment that corresponds to the floor plan, this global and consistent frame of reference is usually not available. In this case, local features such as the walls, the textures and gradients on the floors, and so forth provide the basis for local reference frames. The local reference frames have to be
integrated across space and time to infer the relations between different parts of the building and to gain an understanding of the building’s layout.

Initially, the assignment of a particular reference frame to describe or to encode spatial knowledge might seem like a technicality; after all, information expressed in one reference frame can be easily transformed into another reference frame if the relations between the two frames are known. However, research on spatial memory strongly suggests that the choice of a particular reference frame has important implications in terms of retrieval times and of accuracy of spatial knowledge.

One of the most well-established principles of map placement deals with the conflict of reference frames when interpreting map information. Observers more easily comprehend and use information depicted in so-called you-are-here maps if the up-down direction of the map coincides with the front-back direction of the observer (Levine, Jankovic, & Palij, 1982). In this case, the egocentric front-back reference frame maps directly onto the vertical reference frame used to interpret map information. Other research extended these findings to memorized information. When viewing a path with multiple segments from one particular viewpoint, retrieval of spatial knowledge from memory is easier when observers must judge spatial relations from a heading parallel to their original perspective than from other headings (Presson & Hazelrigg, 1984). Because of the dependence of memory retrieval on the original heading during the learning phase, these effects are termed alignment effects (also see Shelton & McNamara, 1997). Recent studies have shown that apart from the initial heading during learning, which can often provide a reference direction, the geometry of the spatial context can have a large effect on the preferred reference direction and thus on the preferred reference frame. For example, if observers have to learn a configuration of objects within a square room, they will have a much easier time retrieving the spatial directions of the objects when imagining themselves aligned with the room’s two main axes parallel to the walls than when imagining themselves aligned with the two diagonals of the room (Werner, Saade, & Lüer, 1998). Similarly, when asked to point in the direction of important landmarks within the city they live in, participants have a much easier time when imagining themselves aligned with the street grid than misaligned with it (Werner & Schmidt, 1999; see also Montello, 1991). Lastly, when retrieving spatial information about a layout of objects in a sloped environment (e.g., on a hill), participants show a significant preference for headings aligned with the up-down axis of the space more than all other possible directions (Werner, 2001). Additional research strongly suggests that the perceived structure of an environment influences the way a space is mentally represented, even in cases where the acquisition is well controlled and the observer is limited to
only a few views of the space (McNamara, Rump, & Werner, 2003; Mou & McNamara, 2002; Shelton & McNamara, 2001; Werner, 2001). In sum, the evidence clearly favors a view in which the perceived spatial structure determines the selection of a reference frame aligned with this structure. Retrieval of spatial information is most accurate and least effortful in cases where the actual or the imagined heading of a person within the environment matches the main axis of the reference frame used. Other findings that have emphasized the important role of geometrical structure for spatial cognitive tasks come from linguistic studies (Levinson, 1996; Pederson, 1993), animal cognition (Cheng & Gallistel, 1984; Gallistel, 1990; Gouteux, Thinus-Blanc, & Vauclair, 2001), and developmental psychology (Hermer & Spelke, 1994, 1996).

Above, we mentioned that a person navigating a large-scale space such as an office building benefits from knowledge of the spatial relations among parts of the environment or objects therein. Even though there are different navigational strategies not all of which depend on global spatial knowledge (Allen, 1999; Gillner & Mallot, 1998), the ability to locate oneself within a larger context is usually seen as a helpful additional source of information (Werner, Krieg-Brückner, & Herrmann, 2000). Keeping track of one’s location in the built environment often requires the integration of spatial information across multiple places. Expressing spatial relations within the same reference frame is an efficient way to integrate spatial information (for a formal model derived from the animal literature, see Poucet, 1993). A common reference frame enables a navigator to relate spatial information that was acquired separately (e.g., by traveling along a number of path segments).

The following experiment tests the main proposition of this article by examining the effects of aligned and of misaligned local reference frames in a number of way-finding tasks. The motivation for the experiment was derived from two sources. First, the findings in the basic research literature show large effects on memory tasks, such as pointing or naming of objects in more or less artificially restricted environments. In this experiment, we wanted to test whether the established cognitive costs of misalignment in spatial memory would also determine the performance in a real-world task such as way finding. Second, the first author was asked to consult on an improved signage system for an office building that was generally perceived as having low architectural legibility and significant way-finding problems. One of the factors presumed to be responsible for the way-finding difficulties people experienced in this particular building was the misalignment of the central part of the circulation system. For the main manipulation in the following experiment, we therefore varied the alignment of the central part of the building to be aligned or misaligned with the rest of the building. According to our
analysis above, integration of spatial knowledge gained through active navigation should be easier when the local reference frames of all regions are aligned with each other than when the central region is misaligned. This, in turn, should be reflected in increased way-finding performance (speed or accuracy) and a better global understanding of the building’s layout.

**METHOD**

**PARTICIPANTS**

Fifty-six college students participated in the study for course credit or for $8 compensation. The participants’ ages ranged from 18 to 48 years (M = 20.6). Twenty-eight participants were female; 28 were male. All participants signed an informed consent before starting the experiment.

**MATERIALS**

Four separate, synthetic environments representing a single floor of a complex office building were prepared for the study. They were modeled using Maxton’s 3D Studio Max R3 software package and exported as .wrl files to be displayed in a standard Web browser (Netscape 4.7) with a Cortona VRML client V 3.1 plug-in. The four models differed only in the floor plan layout. Textures for the walls, floor, doors, and other materials were identical across environments. The basic environment was generated using the floor plan from an existing office building (town hall) in Göttingen, Germany. The modeled floor contained approximately 54 offices. The remaining three environments were designed to vary along two separate dimensions. The most important change concerned the orientation of the circulation entrance of the original floor plan around the elevator. In the original building, the area containing the elevator and the surrounding hallway is misaligned 45° with respect to the rest of the building (see Figure 2, top left). For the corresponding aligned environment, this region was altered to align its orientation with the main building (Figure 2, top right). This change constitutes the first experimental variable (alignment). As a second manipulation, we modified the clipped corners of the original floor plan to rectangular corners (see Figure 2, bottom row). We thus designed two new environments based on the previous two by changing the existing 45° corners to 90° corners. This modification constitutes the second variable in our study (corners).
Five target objects were added to each floor plan. They consisted of differently colored spheres on pedestals, which were placed in small nooks or short dead-end hallways within the building (see Figure 3 for target-object locations). All of the target objects were located in such a way that they were hidden from view unless the participants were directly in front of them. To avoid confusion about the naming of the colors, we added a small label indicating the name for each target color below each sphere. In addition, a space in front of the central elevator was marked by a textured circle on the floor (indicated as Location 1 in Figure 3).

The length of individual hallways and the location of a subset of intersections varied slightly across floor plan layouts. We minimized these changes across the different floor plans and kept the overall feeling of the office building environment as similar as possible within the constraints of our $2 \times 2$
factorial design. In addition, we ensured that the location of the five target objects and that the floor marking in front of the elevators were in exactly the same spatial locations in all four environments.

Two practice mazes were used to give participants an opportunity to familiarize themselves with navigating a synthetic, computer-generated environment. The interface used for navigation consisted of a regular computer mouse. The position of the cursor within the display window determined the direction and the speed of navigation. The first practice maze required navigating in an open space, traversing through numbered gates in the correct order. This slalom maze provided a challenging spatial environment in which precise navigation was necessary to complete the task. The second hallway maze required following a designated path through hallways similar to those used in the actual office-building environments. Participants
had to follow arrows through a network of hallways while avoiding protrusions on the walls, which simulated the door jams in the environments tested.

The mazes and the experimental environment were displayed in a 600 × 400 pixel window on a 22-inch Iiyama Vision Master Pro 510 monitor running at 85 Hz and at a resolution of 800 × 600. The frame rate varied depending on the amount of rendering that needed to be done but allowed for smooth movements through the environment. Navigation times were recorded using a stopwatch. Response times and accuracy in the spatial-memory task were recorded by a Macintosh PowerPC 7100 using a Gravis ADB Joystick II.

To test participants’ senses of the layout of the building, a set of 16 schematic floor plans was constructed from which participants had to choose the ones that best resembled the experienced building. Besides the four floor plans used in the study, four additional floor plans with a changed topology were included as distracters. In these cases, the two regions of the main building were depicted as disconnected. Finally, each of these eight floor plans was depicted in two different orientations (0° and 45°) resulting in 16 different plans (see Figure 4).

PROCEDURE

At the beginning of the experiment, participants were familiarized with the navigation interface used for the synthetic environments. The experimenter demonstrated the function of the mouse, and participants briefly tried moving around in a large, empty room displayed on the monitor to demonstrate that they understood how the interface worked. Participants then navigated both practice mazes multiple times to improve their navigational skills. Participants were required to complete the slalom maze at least twice and to continue until they required less than 3 minutes to complete it. No participant required more than three trials to achieve this criterion. Similarly, participants had to complete at least two runs through the hallway maze and had to achieve the time criterion of less than 3 minutes before continuing on. The experimenter recorded completion times for each of the mazes.

Learning phase. After familiarizing themselves with the interface, participants explored the experimental environment for their condition. Participants were randomly assigned to one of the four floor plans. They were instructed to explore the building until they felt familiar with it and to learn the locations of the five target objects that were placed throughout the building. Participants were required to explore the space for a minimum of 10 minutes but were allowed to explore for up to 20 minutes if they felt that they
needed to. If they did not locate all of the five objects within 5 minutes, they were directed to them by the experimenter.

Way-finding task: After completion of the learning phase, participants’ way-finding performances in the learned environment was tested on 30 different way-finding tasks. The first 10 way-finding tasks required the participants to find their way as quickly as possible from the marked location in front of the elevator to each of the five target objects. For each task, the experimenter selected the elevator as the starting point, which was then displayed on the monitor as the initial view the participants experienced. The target color that the participants had to find was verbally indicated. The experimenter recorded way-finding time (in seconds), starting with the naming of the destination color. Each task was given twice. The remaining 20 tasks started the participants randomly at one of the target-color locations. In this case, the participants did not know their starting point until the experimenter told them the destination that they had to find (another target color). As before, the experimenter selected the starting viewpoint to be displayed on the monitor.

**Figure 4:** Set of 16 Schematic Floor Plans That Participants had to Choose From
NOTE: The top two rows show the four floor plans used in the experiment. Plans in row two are rotated by 45°. The lower half of the set shows the topologically incorrect versions.

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Pointing task. After completion of the way-finding tasks, participants were tested for their global configural knowledge of the environment that they had learned. Participants were asked to imagine themselves at one of two locations within the environment (in front of the elevator or at another hallway intersection; see Locations 1 and 2 in Figure 3). They were then instructed to imagine themselves facing a particular direction. To enhance this instruction, the corresponding view within the environment was also displayed on the computer screen. After they indicated that they had mentally aligned themselves with the required orientation, participants were probed with the verbal labels for the target colors in random order. The participants’ tasks consisted of pointing with a joystick as quickly and as accurately as possible in the relative direction of the named target color with respect to their imagined orientation. Each target color was tested four times, and participants were tested in four different orientations in each location. Half of the participants were tested from the elevator location first and the other position second, whereas the other half were tested in the opposite order. The program recorded pointing latencies (reaction times in milliseconds [ms]) and pointing accuracy (in degrees). To avoid problems with the pointing task, participants were familiarized with the joystick as a pointing device and the general procedure in a few practice trials using cardinal directions without reference to the experimental environment.

Floor-plan selection. At the conclusion of the experiment, participants were asked to identify the general floor-plan layout from the display of 16 different floor-plan depictions. Each participant was encouraged to pick and to rank the four floor plans that in their view best depicted the environment they experienced. The experimenter recorded the numbers and the order of the selected plans.

The total time for the experiment ranged between 1 hour, 15 minutes to 2 hours, 30 minutes, depending on the time taken by the participants to complete the way-finding and pointing tasks. If requested by the participants, short breaks were allowed at the transitions between the different tests.

RESULTS

WAY-FINDING PERFORMANCE

The recorded completion times for the 30 way-finding trials were averaged for each participant. No trimming of the data was performed. The
average time for a way-finding trial was $M = 41.0$ s ($SD = 24.7$ s). Individual average way-finding times during the test ranged widely between 13.5 s and 148.0 s. The large range of way-finding times was partly a consequence of the varying abilities of participants to navigate a synthetic environment with the mouse as a navigational interface. Although at least four practice runs in two different environments were completed by the participants prior to the main experimental trials, these training episodes reduced but did not eliminate large interindividual differences in navigational competence. We therefore included the completion time of the second hallway maze, which was completed by all participants, as a covariate in all analyses of way-finding times in the hope to eliminate a large part of the interindividual variance because of different traveling speeds.

The average way-finding times were submitted to a $2 \times 2$ between-subjects ANOVA, with the completion times for the second hallway maze as a covariate. The value of the covariate for one participant had to be estimated through linear regression from the performance on the first slalom maze because it was not recorded. The covariate had a significant effect, $F(1, 51) = 21.34, p < .001$. On top of these large interindividual differences, the factor alignment showed a significant influence on way-finding times, $F(1, 51) = 4.68, p = .035$. Average way-finding times in the two aligned conditions were considerably lower ($M = 35.8$ s, $SD = 15.6$ s) than in the two misaligned conditions ($M = 46.2$ s, $SD = 30.7$ s). The factor corners showed no reliable effect, $F(1, 51) = 1.57, p = .215$. Way-finding times were slightly shorter in the clipped-corner condition ($M = 37.9$ s, $SD = 15.2$ s) than in the modified orthogonal condition ($M = 44.1$ s, $SD = 31.5$ s). A summary of these results is given in Figure 5. However, because the average length of hallways in the orthogonal corner condition was approximately 3% longer than in the clipped-corner condition and because navigation around clipped corners might be easier than taking a $90^\circ$ turn, the physical changes between the two conditions might be responsible for these differences. An analysis of average speed revealed that the conditions (orthogonal vs. clipped corners) were navigated with nearly identical speed (819.0 units/s vs. 818.9 units/s). The interaction between alignment and corners was not significant, $F < 1$.

**POINTING ACCURACY**

For the analysis of pointing accuracy, two separate analyses were performed, one for each of the locations from which participants had to imagine pointing to the objects (either directly in front of the elevator or at the other location in the main hallway; see Figure 3 for details). Because of experimenter error, three sets of pointing data for the elevator location and one set
of pointing data for the hallway location were corrupt and could not be included in the analyses. Average pointing accuracy was $M = 42.5^\circ$, $SD = 26.0^\circ$ (range = 16.0$^\circ$ to 126.1$^\circ$) for pointing judgments from the elevator, and $M = 50.1^\circ$, $SD = 22.9^\circ$ (range = 20.0$^\circ$ to 101.7$^\circ$) from the other hallway. Analogously to the way-finding tasks, absolute pointing error for both locations was submitted to 2 (alignment) × 2 (corners) between-subjects ANOVA, separated by pointing location. No covariate was used in this case. The factor alignment had a significant effect on pointing accuracy for pointing judgments from the elevator, $F(1, 49) = 14.31, p < .001$ but was not significant for pointing judgments from the other hallway $F(1, 51) = 2.37, p = .130$. No other main effects or interactions reached significance ($F$'s < 1, except the alignment × corner interaction for pointing judgments from the hallway, $F[1, 51] = 3.11, p = .084$.)
was better in the aligned case ($M = 30.8^\circ$, $SD = 13.2^\circ$) than in the misaligned situation ($M = 54.7^\circ$, $SD = 30.5^\circ$). Pointing accuracy in the clipped-corner condition was slightly lower ($M = 45.3^\circ$, $SD = 30.1^\circ$) than in the orthogonal condition ($M = 40.0^\circ$, $SD = 22.1^\circ$). For pointing judgments from the other hallway, accuracy again was better in the aligned condition ($M = 45.3^\circ$, $SD = 20.1^\circ$) than in the misaligned condition ($M = 54.7^\circ$, $SD = 24.9^\circ$). Participants in the clipped-corner condition again showed slightly higher error ($M = 52.0^\circ$, $SD = 24.2^\circ$) than in the orthogonal corner condition ($M = 48.1^\circ$, $SD = 21.8^\circ$). The results are summarized in Figure 6.

RANKING OF FLOOR PLANS

Four binary factors were used to construct the set of schematic floor plans from which the participants had to choose and to rank order the environment that they had experienced. In each group, each person had to name one first choice (for a total of 14 top choices) and named an additional three plans as ranks two through four (for a total of 56 choices per group, or 112 choices per condition). The four groups did not differ significantly in their absolute accuracy in identifying the correct floor plan that they had encountered—neither as their top choice (range = 3 to 4 participants who chose the correct plan per group) nor as one of their top four choices (range = 5 to 8 participants per group), $\chi^2 < 1.46$, $p > .5$. Participants only minimally preferred aligned plans to misaligned plans. In the aligned condition, 14 people chose an aligned plan as their top choice, whereas another 14 chose a misaligned plan. For the misaligned condition, a small preference (11:17) for the misaligned plans was observed. This difference in selection was not significant. Total choices were also indistinguishable between conditions (60:52 for aligned plans, no matter whether the experienced environment was aligned or misaligned). Participants who had experienced the environment with the original clipped corners showed a strong preference to select floor plans that were clipped (25:3 for top choices, 96:16 for total choices), whereas participants who had experienced the modified orthogonal floor plans did not discriminate strongly along this dimension (16:12 top choices with orthogonal corners, 56:56 total choices). This difference in sensitivity to the shape of the corners was significant, $\chi^2 = 7.38$, $p = .007$ for top choices, $\chi^2 = 32.7$, $p < .001$ total. On the other hand, participants who had experienced the clipped corners were less accurate in choosing the correct topology or the floor plan (15:13 for top choices, 64:48 for total choices) than were participants who had experienced the modified orthogonal conditions (22:6 for top choices, 83:19 for total choices), $\chi^2 = 3.90$, $p = .048$ for top choices, $\chi^2 = 14.57$, $p < .001$ total. Alignment condition did not have any effect for this dimension. Finally,
significantly more participants in the aligned conditions chose floor plans depicting the elevator in an upright orientation as their top choice (20:8 as top choice, 58:54 for total choices) than did participants in the misaligned conditions (10:18 as top choice, 52:60 for total choices). This difference is significant for the top choices only, $\chi^2 = 7.18, p = .007$.

DISCUSSION

The results of our study indicate that misaligned local reference frames within a building substantially impair way-finding performance. Average way-finding time was significantly slower (by almost 10.5 s, or approximately 25%) in those experimental conditions in which the central part of the circulation system—the region around the elevator—was misaligned with respect to the rest of the building. In addition, the lower way-finding performance in these conditions was mirrored by a lower pointing accuracy when pointing to other parts of the building from the elevator region. Participants’ pointing error from this location was 23.9° greater (approximately 75%) in the misaligned conditions than in the aligned conditions. This result shows that participants in the misaligned condition experienced severe problems
orienting themselves with respect to different parts of the building when they had to judge directions across the two reference frames—the orientation of the elevator region and the orientation of the rest of the building. When pointing from the second location in the building, this advantage for the aligned conditions was reduced to a nonsignificant difference of 9.4°, or approximately 20%. Participants in the aligned conditions performed slightly better, even though the pointing task in this condition mainly consisted of judgments within the same reference frame. In sum, the results suggest that integration of spatial knowledge gained through a number of local views while exploring a building is more difficult and error prone when local reference frames are misaligned.

In addition to the main findings relating to way-finding and to pointing performance, the choices of floor plans from the list of 16 plans allow some interesting observations. In general, participants were not very successful in their attempts to correctly identify the environment that they had learned. Only about 35% of participants were able to select the plan that they had experienced. This demonstrates the difficulty of matching one’s immersive spatial experience to a two-dimensional representation of the experienced space. Unlike other studies, which showed proficient configurational knowledge of the environment to be learned (e.g., Gärling, Böök, Ergenzen, & Lindberg, 1981), the poor performance in this study can probably be traced to the systematic variation of depictions along four separate dimensions. This produced a very homogenous set of targets and of distracters, making the task more difficult. Most importantly, the alignment factor that showed a substantial effect on way-finding and on pointing performance did not seem extraordinarily relevant for participants’ selections of a plan. This implies that participants did not attend to this feature of the plan consciously, even though it did play a role in their ability to integrate spatial knowledge successfully.

With respect to the perceived orientation of the space, which is of particular relevance to the topic of spatial reference frames, the data is ambiguous. Although participants in the aligned group preferred a plan that depicted the elevator in a square orientation, the misaligned group preferred the elevator region to be in a diamond orientation (rotated by 45°). However, this differential preference might be a consequence of participants of all groups, on average, favoring depictions of the main parts of the building in a horizontal orientation. In the misaligned case, the correct choice of plan in this case would lead to a 45° tilted elevator. It is important to note that the absolute orientation of the floor plan was arbitrary in this study, whereas the relative orientation of the parts was not. Participants’ preferences for one or for the other orientation of the entire plan therefore merely indicate their cognitive preference for one orientation.
The design choice of clipped versus orthogonal corners had a significant impact on how the topology of the building was remembered. Participants in the orthogonal conditions strongly preferred the correct, connected plans, whereas participants in the clipped-corner condition were less sensitive to this dimension. It seems that the clipped corners made it more difficult for participants to gain a general understanding of the building.

Overall, the results provide evidence that the orientation of different parts of a building can be an important factor in way-finding performance and therefore in the usability and the positive experience of a space. Misalignment of local reference frames, as investigated in this study, led to a deterioration of way-finding speed and to a decrease in pointing accuracy, indicating that participants were less clear about the relations between different parts of the building. The study therefore succeeded in its main goal; it applied recent findings from basic spatial cognition research to an applied way-finding situation. More importantly, however, the study allows us to draw a few important conclusions for designing more navigable spaces. The spatial relations, especially differences in orientation between different parts of a building, seem to play a role in how humans are able to organize and to integrate spatial knowledge. Unlike other formal approaches, which have mainly taken a topological or graph-analytical approach (Hillier, 1996; O’Neill, 1991), this article stresses a geometrical property of space, namely, orientation. Based on our results, formal geometrical analyses of spatial structure might be extended to include information about shape and orientation to make them more cognitively plausible (e.g., Peponis et al., 1998; also see Montello, 1998, for an analysis of the importance of metric spatial relations, such as distance and relative location, for human spatial navigation).

Architectural design for way finding should pay attention to the preferred assignment of reference frames for different parts of a building to reduce cognitive workload on the side of the user and ease the integration task across different places. Architectural design can aide this integration process by assuring that the perceived spatial structure in each part of a building is encoded in aligned spatial reference frames and thus is consistent with a global structure or frame of reference. This does not imply, however, that buildings have to be organized around a simple orthogonal grid with only right angles. Other, more irregular designs are unproblematic as long as the architect can achieve a common reference frame by making common axes salient. This can be done by exploiting other geometrical properties, such as symmetry axes, elongation, use of visual textures, or even functional orientation. In addition to helping people find their way, a globally consistent frame of reference is also beneficial for providing way-finding aids, such as you-are-here maps (Werner & Jaeger, 2002). An alternative approach to this
problem might use globally visible structures, such as an atrium, the outside landscape, or other prominent features, to provide a salient, global frame of reference that allows for the integration of different places within it. By making the global frame accessible from within each place, integration should be much easier and more robust while at the same time allowing for more creative freedom for the architect.

NOTE

1. Unlike the statistical tests for top choices, the interpretation of the $\chi^2$ values for total choices is problematic because the data points are not fully independent of each other (each participant produces four total rankings).

REFERENCES


