Virtual Reality in Mobility Design

Experimental Research on the Application of VR Simulations

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For the design of public mobility, the perspective of users is fundamental: how can their needs and expectations be integrated into the design process? By virtue of their spatiotemporal experiential quality, virtual reality simulations have the potential to convey the actual impact of designs and planning measures on users more effectively than traditional forms of representation such as renderings or plans. Through collaborations between experts from the areas of cognitive psychology and design research, the research project »Cognition Design« (CogDes) explored the questions: to what degree are virtual reality simulations adapted to investigating the impact of design decisions on users? And: how realistic do such simulations need to be if they are to lead to well-founded conclusions concerning the impact of the simulated situations on users? The research project is a joint project of the Scene Grammar Lab of the Department of Psychology at the Goethe University in Frankfurt and the Design Institute for Mobility and Logistics at the University of Arts and Design Offenbach.[01]

Virtual Reality Simulations as Test Environments

When it comes to determining the impact of design decisions on user perceptions, new technologies in virtual reality (VR) appear quite promising. These make it possible for users and researchers to encounter one another in a simulated space featuring a high degree of realism. VR simulations have features that make them especially well-suited to investigating complex perceptual processes. First, so goes this argument, they are immersive in a way that is impossible for either laboratory environments or renderings and plans to achieve. This makes it possible to compare actions and experiences in real space. In VR, secondly, it becomes possible to compile comprehensive scientific data in a controlled way: the simulation of various mobility environments with a range of variants facilitates a systematic investigation, based on cognitive psychology, of the impact of design decisions (for example, lighting and lighting control, object positioning and object design, surface design, the arrangement, density and design of information in the form of images and texts, spatial structuring, etc.) on users.

If it is indeed true (to return to our initial question) that the virtual environment, with its spatiotemporal experiential quality, is genuinely comparable to experiences in real space, this would make it possible to develop a valid foundation for design decisions on the basis of tested spatiotemporal multiuser experiences. From the perspective of design research, then, VR simulations make it possible—at a relatively low cost—to test planning and design variants for mobility spaces and hubs systematically with the assistance of methods from cognitive psychology (↳Fig. 1).

Virtual reality is an ideal environment for studies in cognitive psychology. VR models are used in psychology to an increasing degree, since they ensure a high degree of experimental control while offering the ecological validity of a realistic, non-laboratory-technical environment. The latest eye-tracking technologies, which are integrated into VR headsets, permit the precise registration of processes of attention in space and time. Through the systematic analysis, both in the real reference

01 The project was sponsored by the German Federal State of Hesse (Ministry of Economy, Energy, Transport, and Housing) and the HOLM Innovation Funding in the framework of the measure »Innovations in the Area of Logistics and Mobility« (HA Projekt-Nr. 817/19–137). In terms of content, it arose from the research conducted as part of the LOEWE research cluster »Infrastructure—Design—Society« (sponsored by the Hessian Ministry of Higher Education, Research, Science and the Arts through the Excellence Program of Hesse). The team consisted of research staff and students from the Goethe University in Frankfurt (cognition psychology): Leah Kumle, Leila Zacharias, Teresa Schnorbach, Julia Beitner, Stephen Hinde, Erwan David, and Melissa Le-Hoa Võ (project leader); and the HfG Offenbach University of Art and Design (design): Annika Storch, Luke Handon, Ken Rodenwaldt, Robin Schmid, Julian Schwarze, Kai Vöckler, and Peter Eckart (project leader). Project documentation is available at https://immersitylab.org.

Fig. 1 Experimental research and data collection through the application of virtual reality test environments (Source: Julie Gaston; Julian Schwarze, Design Institute for Mobility and Logistics, HfG Offenbach)

situation as well as in the simulation, psychologists acquire knowledge concerning the ways in which real and simulated situations are comparable, thereby potentially laying the groundwork for subsequent research.

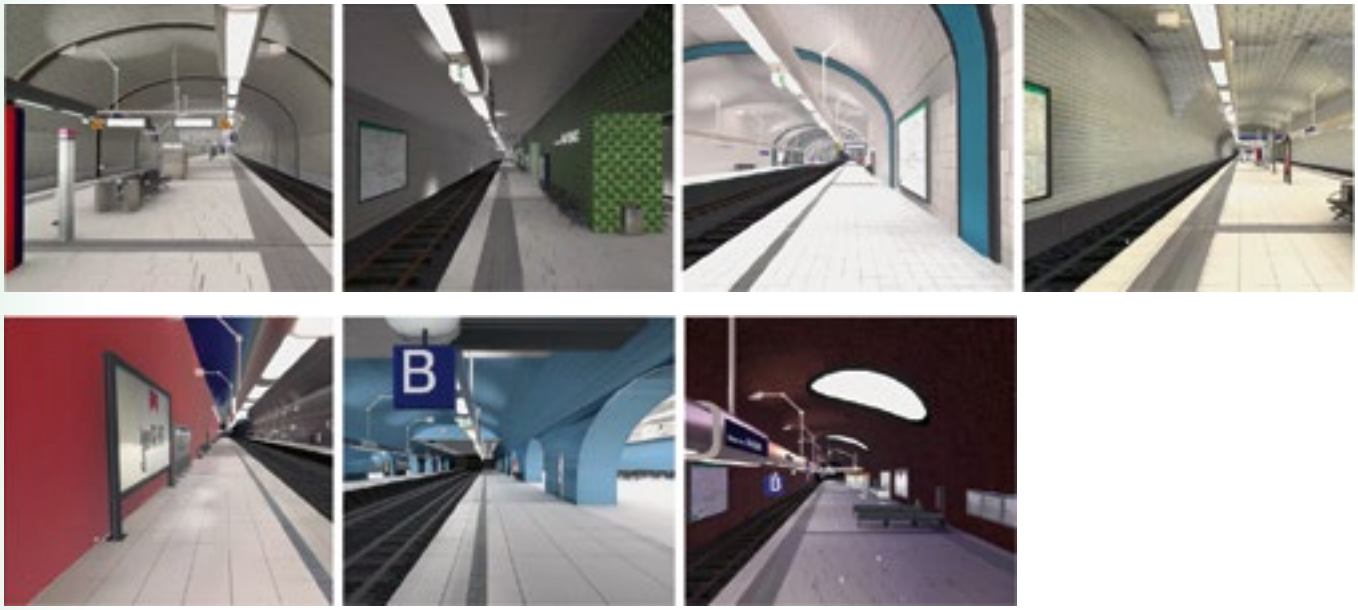
Delimiting the Area of Investigation

Developed and tested in the project, based on a typical mobility situation (the subterranean level of a commuter rail station), are simulations having varying degrees of realism—from a relatively abstract test environment (laboratory situation), all the way to the integration of richly detailed operational, movement-based, and experiential options. The latter might include the greatest possible freedom of movement and extend to the formulation of realistic tasks that are to be fulfilled by the test subject. In order to arrive at reliable conclusions, the focus of the project was on the visual experience of a subterranean, multileveled commuter rail station. The target of investigation was the wayfinding from the entrances to the station via a B level to the train platform, set lower down, subdivided into a sequence of spatial interactions. An analysis of processes of attention, both in the real reference situation as well as in the simulated situation, led to conclusions concerning the degree to which real and simulated commuter rail stations are comparable, taking into account the fact that social interaction could not be simulated in the VR experience. Correspondingly, the investigation focused on individual and psychological experience during utilization. Socioemotional factors of influence and symbolic meanings of the kind that emerge from the individual's social milieu were not investigated. Previous experience on the part of the test subjects, where applicable, was taken into account, but all olfactory, auditory, and haptic perceptions (and the thermic influences associated with them) were not considered since these could not be simulated, at least not adequately. Therefore, the principal focuses were functional aspects of spatial orientation and the subject's understanding of visual information (textual and graphic symbols) while navigating the mobility space, which is essentially dependent upon visual understanding (↳Figs. 2a+b).

Interdisciplinary Methodological Approach

Methodologically, nomothetic and ideographic approaches in the study were interconnected. This encompassed qualitative and quantitative surveys, the tracking of attentiveness, the analysis of behavioral patterns, and physiological and psychological methods of measurement. Quantitative measurements were data from the act of use, while the act of measurement avoided influencing or altering user behavior. The recording of eye and head movements (eye- and gaze-tracking) in the VR environment made it possible to investigate the

Figs. 2a+b Comparison of a real space and its digital twin through the application of virtual reality technology and eye-tracking (Source: Julie Gaston)



Figs. 3a–g Illustration of the seven simulated commuter rail stations, accessible with VR glasses (Source: Design Institute for Mobility and Logistics, HfG Offenbach)

influence of various design approaches on attentiveness. Beyond this, eye-tracking technologies were used to classify, categorize, and analyze the simulation and its prominent visual features (salience). The measurement of attentiveness formed an important basis from which conclusions concerning the effectiveness of design decisions could be derived. Interpretative phenomenological interviews (interpretative phenomenological analysis, IPA; Smith 2009) allowed the phenomenological experiences of users to be taken into account. These were correlated with the results of quantitative measurements. The research project linked together analytical approaches from design theory (theory of product language) with the experimental analytical methods of cognitive psychology (scene grammar), and transferred these onto a three-dimensional, experiential test situation; findings concerning wayfinding from architectural and design theory were integrated as well. The objective was to produce a scientifically valid basis for the evaluation of design measures and their impact on users. The project should therefore be regarded as experimental basic research.

Theoretical Background

In a first step, the project partners merged their various theoretical approaches and derived the structure of the investigation from the results. In cognitive psychology, the term *scene grammar* (Võ 2021) refers to an approach that defines hierarchically structured rules that are associated with a visual scene (the space), which then facilitate object perception as well as visual search. These rules are extracted from specific episodes of spatial interaction and allow us to make predictions about the location of objects, while facilitating our perception of objects and directing visual attention efficiently within the space. The term *grammar* refers to the analogy between the way in which we learn scene grammar and the way we learn a mother tongue. In both cases, no explicit training is required; instead, expertise is acquired through continuous interaction with the environment. Like a language, this type of grammar can be applied to completely new situations (with language, unknown sentences; here, unknown spaces), thereby facilitating our understanding and interpretation of and interaction with them. A number of valid studies of scene grammar demonstrate that this functions effectively in relatively well-ordered artificial environments such as living rooms and kitchens (Võ et al. 2019; Võ, 2021). Lacking, however, are studies that show how

scene grammar functions in public environments such as train stations, airports, and shopping centers, and in the corresponding VR simulations. The focus on a test environment in the context of public local mobility raises the question of whether this approach is genuinely suitable.

The theory of product language, developed in the late 1970s at the HfG Offenbach University of Art and Design, defines the functions of products as resulting from an interaction between human and object, and distinguishes between practical and »product language functions« (Gros 1976, 1983). Belonging to product language functions are formal-aesthetic functions on the one hand and indicating and symbolic functions on the other. The formal-aesthetic functions pertain to syntax, which is to say to the product's formal structure, and hence to the product's sensual-perceptible characteristics, independent of its substantive meaning (Steffen 2000). But it is not a question here of a set of rules, as with the grammar of a spoken or written language where linguistic units are combined according to conventions (through fixed linkages: syntax). Instead, the formal-aesthetic functions pertain to structural and formal features of products and the ways in which these are interpreted as forms in acts of perception. Inherent in the perception of products is the mostly unconscious, cognitive processing and evaluation. Attention to the theoretical background of scene grammar and to the empirical results it yielded resulted in an expectation of heightened validity for the method of investigation, based on product language.

Experimental Set-Up and Procedure

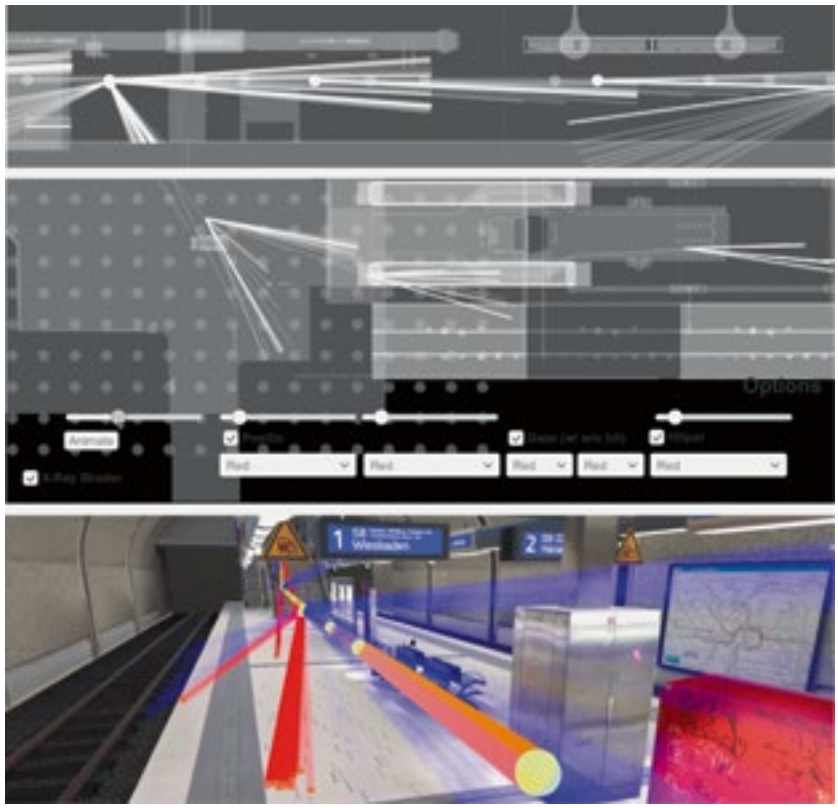
Perceptual and cognitive processes were investigated through VR simulations. This proceeded in two steps, each with a specific research focus:

1. A comparison between the real situation and the virtual reality simulation (current situation) sought to evaluate the validity of the investigation itself; the focus was on the impact of the simulated space and the VR technology (immersion character and sense of reality).
2. Various design measures and their impacts on users (with respect to orientation in space and of information acquisition) were investigated using VR test environment. Then a further six spatial variants were developed on this basis of the digital twin of the real situation.[02]

The point of departure was a digital twin of the Offenbach Marktplatz Station, which made it possible to carry out tests and cross-comparisons between a real situation and its virtual double. In order to record and measure immersive experience in the simulation, it became possible to develop virtual-reality variants for quantitative eye-tracking tests and follow-up qualitative surveys. The developed VR model (»testbed«) consists of seven stations, each with three levels: an entrance level beginning at street level (Level A), an intermediate level with service offerings and waiting areas (Level B), and a platform level for arriving trains, waiting areas, and service offerings (Level C) (↳Figs. 3a–g).

Eye-tracking technologies were used in both the simulated situation as well as in the real reference situation, making it possible to analyze the cognitive influences of design decisions as mediated by degrees of attentiveness. It was also a question of evaluating the ecological validity of the VR test situation in comparison with its real twin. This

02 The COVID-19 pandemic required adaptation of the virtual-reality testing and eye tracking. In response to the necessary hygiene measures, the number of subjects for virtual reality testing was reduced to sixteen, and for testing in the real situation, to just three. In terms of age and social status, moreover, the group of test subjects was fairly homogenous: the participants were primarily students (eighteen to thirty-five years of age) and would need to be more strongly differentiated in subsequent studies. Individuals with physical limitations should be a priority of investigation. In our view, the selection and number of test subjects for investigating the functionality of the virtual reality simulation in the test situation was adequate, and made it possible to arrive at a basic assessment.



Figs. 4a–c Representation of eye-tracking and walking routes and visualization of data gathered during the VR experiment (Source: Ken Rodenwaldt, Design Institute for Mobility and Logistics, HfG Offenbach)

then formed the basis for a continuing investigation of design measures and resources in the correspondingly varied test situations. Eye movements measured visual attentiveness and individual »task performance,« that is, success in achieving certain set tasks. Data on eye movements with respect to their spatiotemporal distribution in real and virtual space were then studied by comparing scan paths or fixation distributions. This made it possible to infer that the respective patterns of attention corresponded structurally (although the validity of these conclusions were limited given the reduced number of available test subjects due to the COVID-19 pandemic). Each station was allocated a specific navigation question, which the test subject was expected to fulfill. The data generated by the test subjects in the seven commuter rail stations, which was recorded and used for evaluation purposes, resulted from positional data, the various velocities of forward movement, as well as head and eye movements (↳Figs. 4a–c).

Juxtaposition of Real Space and Digital Twin (VR Simulation)

Investigated through a comparative analysis was the real space (the subterranean Offenbach Marktplatz Station of the commuter rail) and its virtual twin. It proved possible to evaluate three eye-tracking tests in real space and twelve eye-tracking tests in virtual space. A practical problem was the fact that the virtual spaces were multiple times larger than the space of the laboratory within which the test subjects moved. Piloted and tested therefore were various possibilities of forward movement by means of teleportation. Despite this limitation, it proved possible to gather and evaluate valid eye-tracking and positioning data.[03] Conducted and evaluated as well were qualitative surveys with the assistance of interpretive phenomenological analysis (IPA). The purpose of the survey was to determine whether the VR experience seemed authentic to participants.[04] During testing, all the test subjects became accustomed to the new »reality,« albeit with varying degrees of speed. On the whole, submersion in the virtual

Figs. 5a–f Sequence excerpt: visualization of eye-tracking data in the real Marktplatz Station in Offenbach by means of a film. With the help of eye-tracking glasses, it becomes possible to trace the sequences of use of the test subjects and compare these to the data gathered from the VR simulation. (Source: Design Institute for Mobility and Logistics, HfG Offenbach; Scene Grammar Lab, Goethe University Frankfurt am Main)

station (the immersion quality of the simulation) functioned quite well, although a period of time for acclimatization to the VR world—and finally to transition back to the real world—did prove necessary (↳Figs. 5a–f).

Since most of the everyday tasks and activities performed in a real commuter rail station involve navigation behavior, study participants were assigned corresponding tasks. Typically, the sequence of navigation processes encompasses two activities: wayfinding and path integration. These are based on various human cognitive processes (Coutrot et al. 2018; Wiener et al. 2009). Wayfinding is achieved through the information that is available at key decision-making points within the station, where a choice is made between multiple routes. Path integration is an activity of movement between decision-making points (Mittelstaedt and Mittelstaedt 1980). The investigations focused on wayfinding, since it is of greater relevance to the visual relationships between the objects in the station, and hence for the investigation of the role played by scene grammar in public space (↳Fig. 6).

If scene grammar plays an important role in wayfinding within a station, then the placement of and relationship between the elements of the information and wayfinding system, as well as the spatial objects that are designed to aid orientation, should have a significant influence on wayfinding. Analyses of eye-tracking data support the conclusion that navigational tasks display similar patterns of attention regardless of whether they

03 A virtual reality testbed allows researchers to carry out tests using the cognitive psychology method, involving both software and hardware. The test set-up (observing COVID-19 hygiene requirements) was a virtual reality laboratory measuring 30 square meters, within a larger space (the auditorium of the HfG Offenbach), and included a VIVE Pro eye headset, a high-performance computer, and a server for the Unity database to guide the virtual reality simulation.

04 For the Goethe University in Frankfurt, the IP analysis was conducted by Teresa Schnorbach in the context of a Master's thesis.

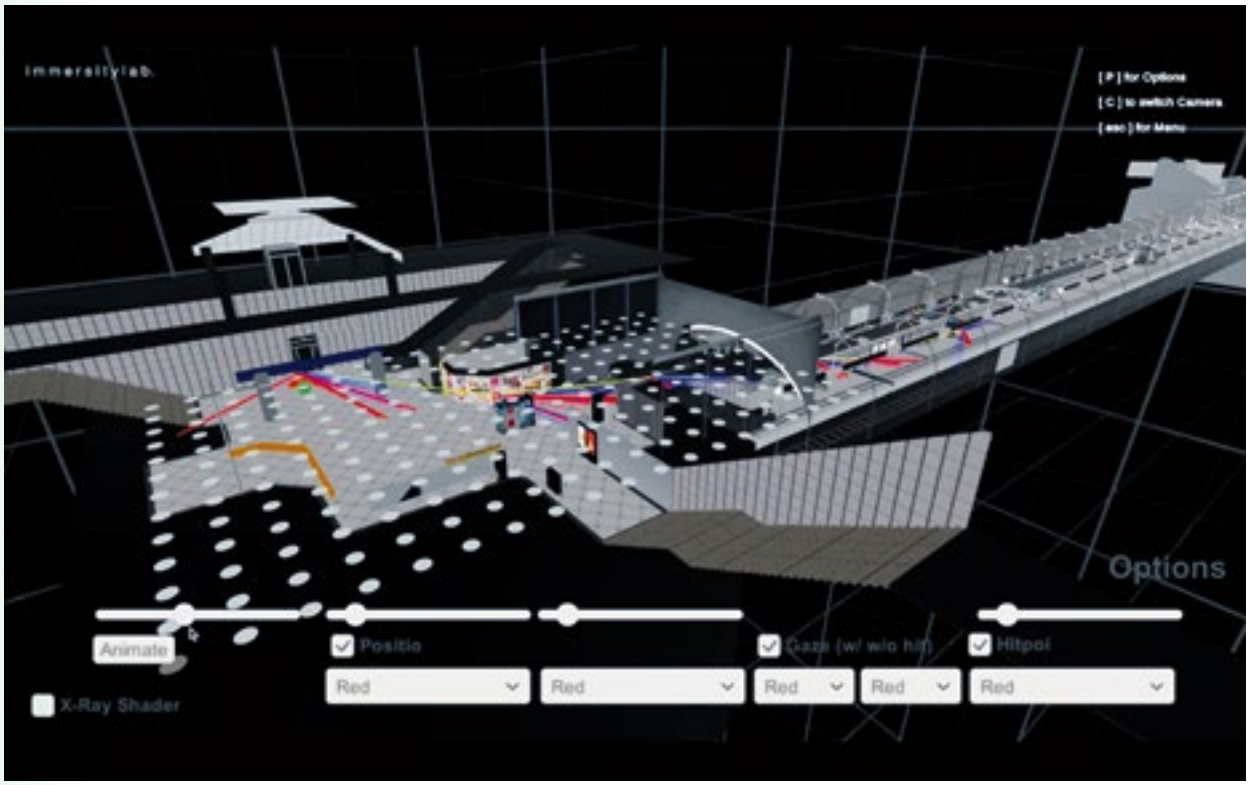
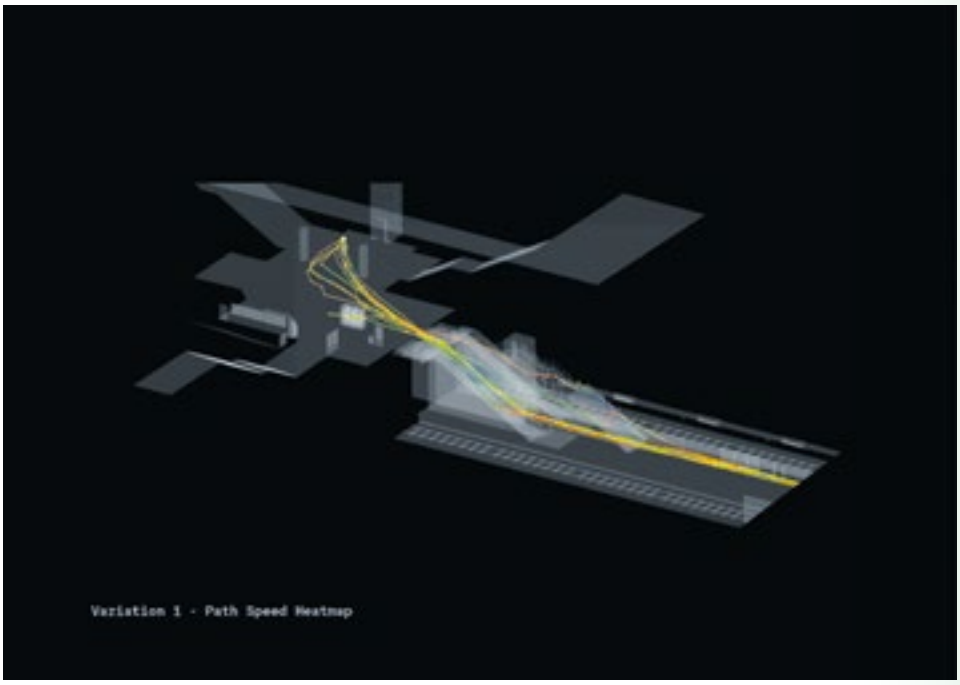


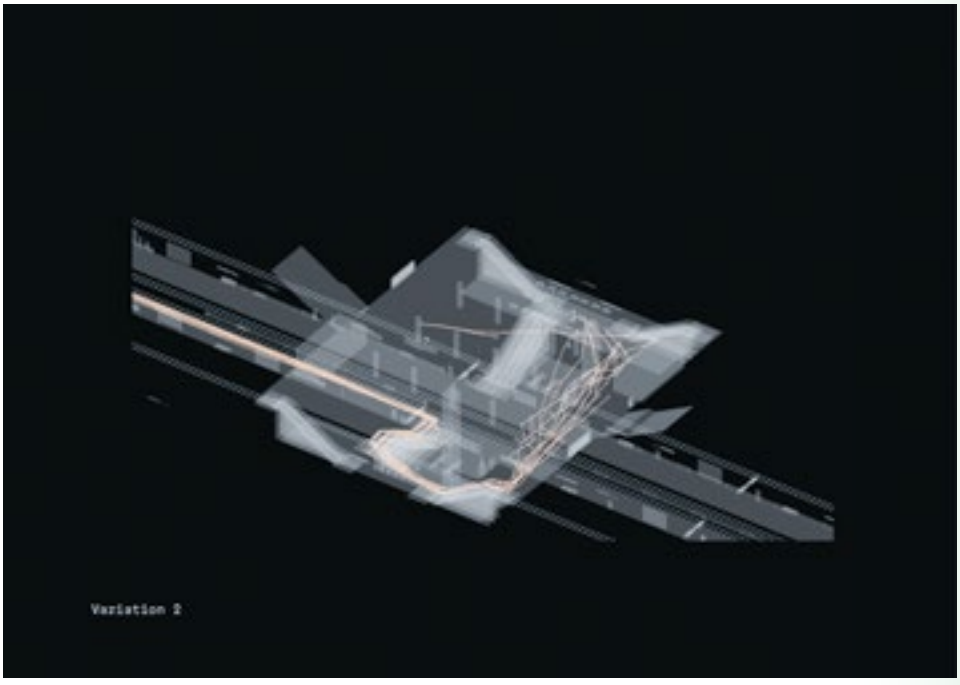
Fig. 6 Eye movements and walking routes can be recorded and evaluated by means of a VR headset. The commuter rail stations are accessible on multiple levels (B levels, subterranean platforms, and staircase crossings). (Source: Ken Rodenwaldt, Design Institute for Mobility and Logistics, HfG Offenbach)

are performed in virtual or real stations. Using measurements based on cognitive psychology and carried out with the help of eye-tracking, patterns of behavior exhibited by the study participants in VR can be juxtaposed with those observed in real spaces. On the basis of a subdivision into wayfinding activities and path integration, certain processes can be precisely defined and compared. The sequencing of search processes is structurally similar in virtual and real space, and corresponding sequences of gazes were observable during attempts at achieving orientation. Clearly, orientation processes proceed similarly in real and simulated spaces. Despite the sequence-altering teleportation processes that take place in digital spaces, both wayfinding processes display similar visual processes of searching and behavior. The comparison highlights the enormous potential of collected eye-tracking data in a spatial situation in the context of mobility and juxtaposes orientation and behavioral processes in both test scenarios (real and simulated) (↳Figs. 7+8).

1. During orientation processes, information elements of the wayfinding systems such as signage are perceived according to the same pattern whether in VR or in real space.
2. During the phase of path integration, which is to say the interval of time after the acquisition of the necessary information and the overcoming of a certain spatial distance, leading to start of the next orientation process, the viewing and movement patterns of test subjects are similar in both VR and real space.

According to the tests conducted, forward movement in VR by means of teleportation—which is to say the overcoming of a large distance through a »leap,« with a corresponding interruption in the flow of movement—had no fundamental influence





Figs. 7a+b The visualization of walking routes can provide information about movement velocity and spatial localization (red = rapid forward movement by means of teleport function = a more limited awareness of the environment). The superimposition of walking routes can also be compared quantitatively. (Source: Ken Rodenwaldt, Design Institute for Mobility and Logistics, HfG Offenbach)

on the comparability of the two worlds. In the path integration phase, which is to say in the time that follows the acquisition of the necessary information and the overcoming of a certain spatial distance, leading to the start of the next orientation process, the eye and movement patterns of test subjects were similar, whether in virtual and real space. This can be concluded as well from the in-depth qualitative interviews. One individual who was quite familiar with the Offenbach Marktplatz Station stated emphatically that when navigating in the digital VR twin, she fully imagined herself to be in the real station. While moving from one space to the next, she found herself scanning her surroundings, searching out all of the features that were familiar to her from the real station.

Based on qualitative interviews, it was concluded that the degree of reality of a VR simulation needed to be different depending upon the question under investigation: while during the process of orientation, the primary attention was directed toward the continuity and recognizability of the key elements of the information and wayfinding systems (the focus of attention was on signage with information in the form of images or text, while the surroundings receded into the background), objects in space that were not of primary relevance for orientation seemed to play a more important role with path integration. The focus of perception was no longer on the orientation system, and perception was directed toward objects in the surroundings (with the gaze sweeping widely). Important here is a heightened degree of reality of the VR simulation since the aesthetic qualities of the space shape experience now in essential ways.

Spatial Orientation and the Influence of Design on Navigation Behavior

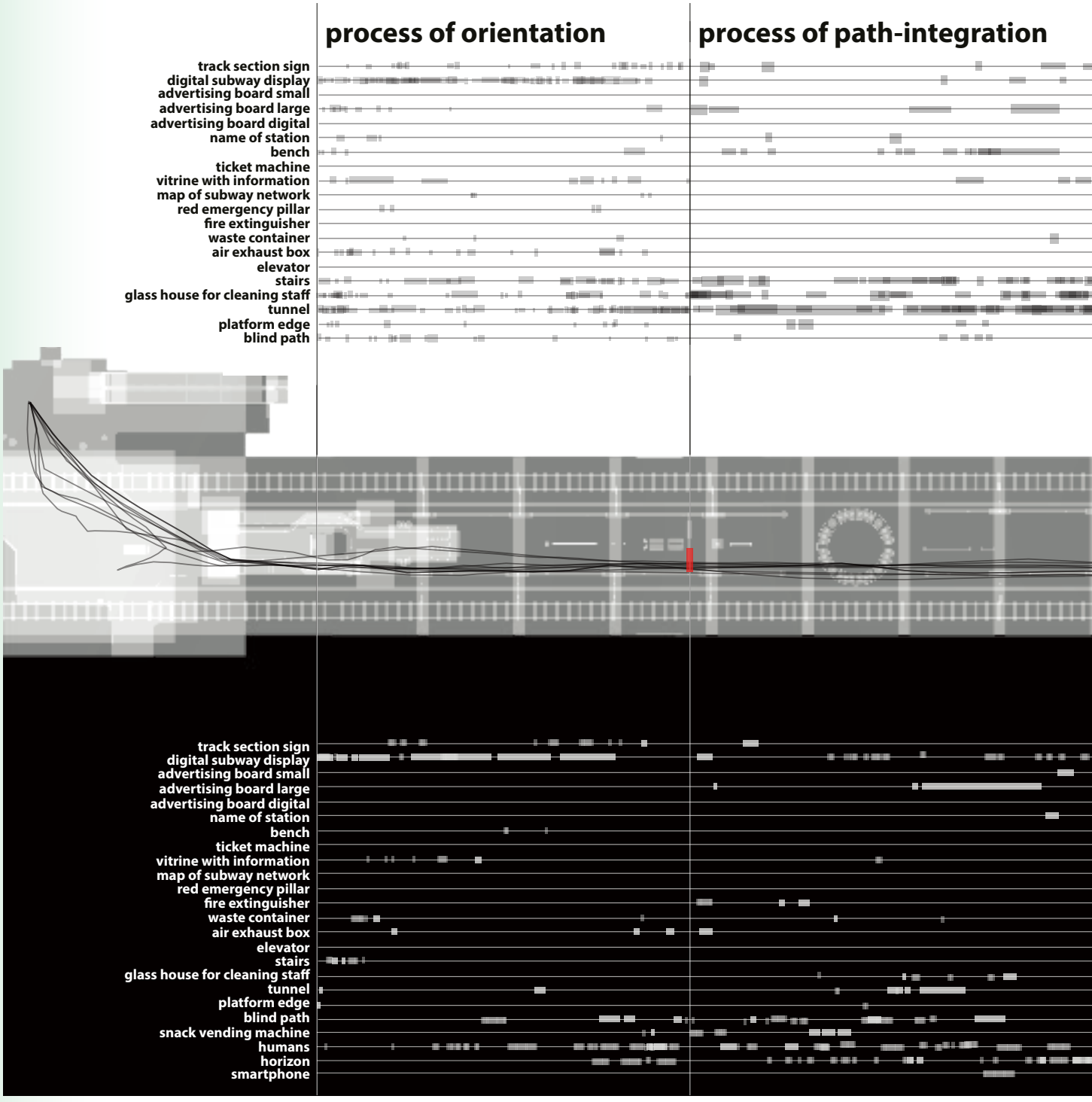
The IPA interviews showed that the study participants used the information and wayfinding system primarily to perform navigation tasks. Meanwhile, additional spatial orientation elements, for example, staircases and exits (spatial openings) had an influence on successful navigation in space. In this context, the formal-aesthetic analysis based on product language supplied important references with regard to the influence of the structure of the spatial environment, including the weighting of orienting elements (concision and distribution in space, the overall density of orientation information, and how that works in relationship to other forms of information not designed to aid orientation). It was not yet possible to fully capture the orienting function of spatial elements. For this reason, there was recourse to the concept of »mental maps,« developed in the field of architectural and planning theory, with their guiding elements designed to structure spatial orientation (Lynch 1960). This refers to the quality of the formal structure of urban space, but also examines interactions between moving users and the built environment in order to identify elements (cognitive map) that are relevant and cognitively effective for orientation (Vöckler 2021). The two components »landmark« and »path« are empirically significant for mental representations and current navigation as they have a high degree of functional meaning and allow little leeway for individual interpretations (Guski and Blöbaum 2008). Particularly relevant to the project's investigative approach was the element »landmark,« which was operationalized here mainly in its function as an incisive optical reference point, one that plays a central role in spatial orientation, and on which users recognizably rely to an increasing degree as soon as a spatial situation becomes more familiar. The identity-forming aspect of landmarks, which often have a symbolic significance in the urban context (historically significant buildings, for example), and their corresponding importance in the memory of spatial situations (mental maps), were factored out. The focus was on the process of wayfinding, which cannot be captured through the evaluation of a schematic or static mental map. Environments are complex entities and are registered and assessed through the goal-directed activities of sequentially structured interactions with the surroundings, as further differentiated in design research into the landmark concept (Arthur and Passini 1992; Vinson 1999; Farr et al. 2012). As analyses of eye movements and fixation points have shown, elements of spatial orientation, including highly visible objects that structure

the space such as columns or freestanding ticket vending machines, serve as optical points of reference that supplement the information elements of the navigation guidance system. Then there are elements such as staircases and spatial openings (entrances, exits), which are of importance for a target-oriented wayfinding, and are not only optically incisive, but also represent decisive spatial offerings for successful spatial navigation (in product language: the indicating functions; reflected on as affordance in terms of design theory; see Norman 1988). The lighting elements, the positioning of other elements of spatial orientation and their visibility, the spatial structure, its visual fields, and the recognizability of elements all make a major contribution to successful wayfinding, and were taken into account in the formation of variants in VR. The importance of the formal-aesthetic spatial structure (ordered complexity) in the act of perception, as reflected to date in the theory of product language only with regard to objects, was also investigated spatially, with due consideration given to the relevant theoretical findings from the fields of architecture and design theory. The focus was on elements that were essential for orientation, as well as their visibility and conspicuousness.

Objects that facilitated orientation—the information elements of the wayfinding system (maps, signage with graphic symbol such as arrows and lettering) and landmarks that serve as optically incisive spatial points of reference (ticket vending machines, columns, staircases, exits, and entrances)—were manipulated within the experiment. Through the formation of diverse variants of the spatial situation, the information and guidance system and the landmarks could be juxtaposed, and their relative importance for the orientation process tested for high contrast and low contrast variables. Factors that influenced attention (distraction, guidance), cognition (orientation, understanding, memory), and emotion (sense of well-being) were investigated and assessed. Navigation relied primarily on the information and guidance systems but the landmarks were also very important in the VR simulations. According to statements by the test subjects, they appeared to define the spatial context in its materiality, which corresponds to the landmarks' function as essential elements of a cognitively processed image of the surroundings, as confirmed by both design research and environmental psychology. They convey the sense to participants that they are dealing with real experience with and in a station. The function of the landmarks (as optically incisive points of reference or markers) resembles the function of anchor objects in the theory of scene grammar (Võ et al. 2019; Võ 2021). Anchor objects are for the most part large and static (i.e., washbasins), which predict the identity and location of other smaller objects (hand soap is generally found *on* a washbasin, a towel *alongside* it), and which constitute a spatial context. Anchor objects therefore play a decisive role in the efficient search for objects in space (Boettcher et al. 2018; Helbing et al. 2022). The spatial context that forms the commuter rail station, for example, is defined by the subjects, and elicits certain behavioral and interaction processes in test subjects. The corresponding object constellations that form landmarks, the spatial-material elements of the architectural fabric; and the information elements that form the wayfinding system, with its images and texts on signage, columns, etc. make localization possible in familiar situations. Their design, in particular through the interplay of the two, contributes in essential ways to successful navigation through spatially complex contexts such as a multileveled commuter rail station, and evidently, generates trust as it ensures an understanding of the spatial situation.

Summary and Outlook

The comparative investigation of a real space together with its virtual twin has demonstrated that the simulation taking place in virtual reality is a well-adapted instrument for researching and recording human experience and movement behavior in a mobility space. Virtual reality can convey alterations to the design of given space, together with its objects and information sources at a low threshold and with a high degree of authenticity (immersive quality). The evaluated results supplied vital information concerning


process of orientation
process of path-integration
track section sign
digital subway display
advertising board small
advertising board large
advertising board digital
name of station
bench
ticket machine
vitrine with information
map of subway network
red emergency pillar
fire extinguisher
waste container
air exhaust box
elevator
stairs
glass house for cleaning staff
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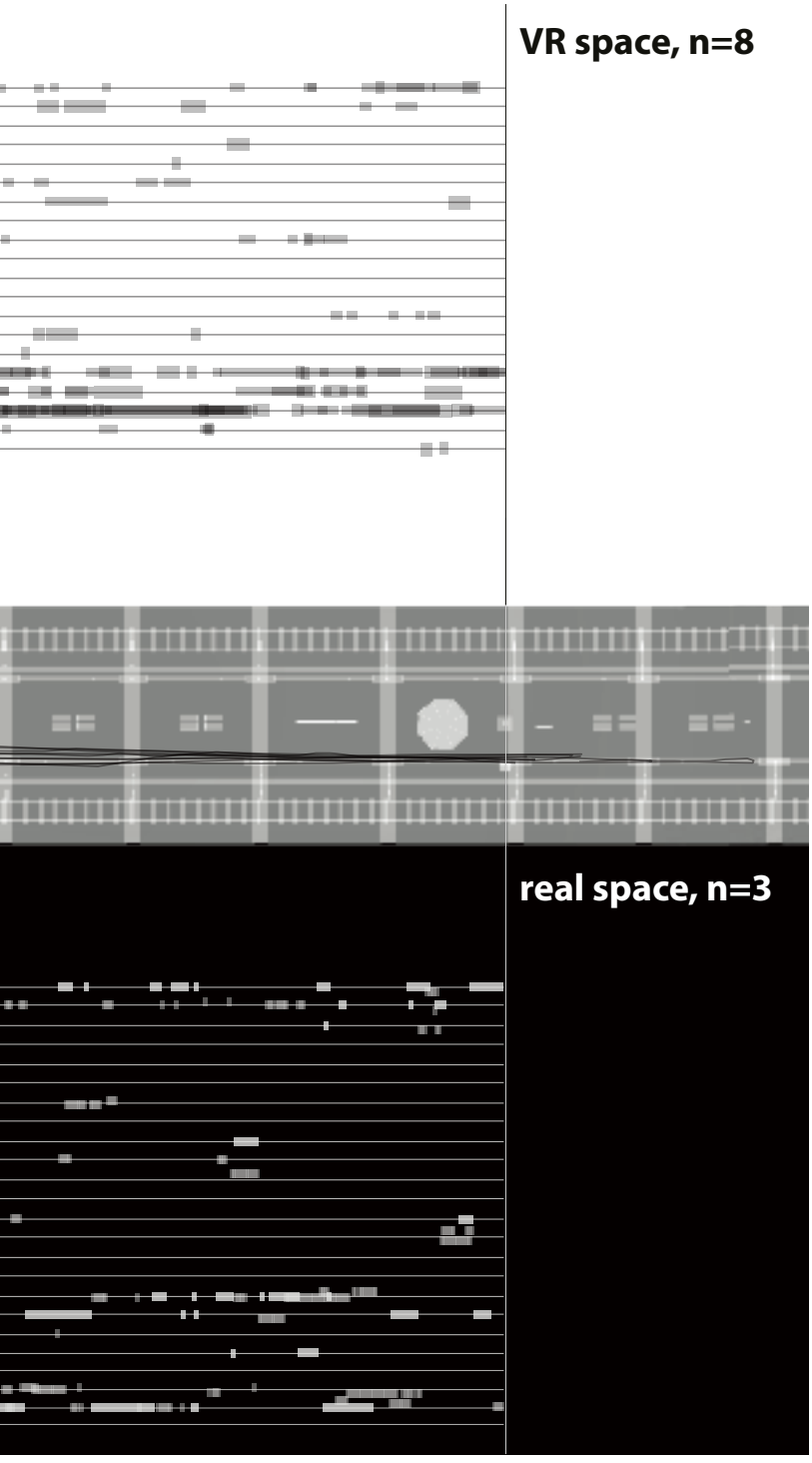

Fig. 8 Comparison of the eye-tracking data collected in VR and in real space. The layout of the platform area of the Offenbach Marktplatz commuter rail station and the B level of the station (eastern entrance), visible at the center, display (as lines) eight of the walking routes covered by the test subjects during the VR experiment. The evaluation shows which objects were viewed by the test subjects during the wayfinding process, and in which area of the station. The data positioned above the layout (black lettering on a white background) shows the objects that were perceived in virtual reality. Depicted below the layout (white lettering on a black background) are the objects that were viewed during the experiment, conducted in the real station. (Source: Julian Schwarze, Design Institute for Mobility and Logistics, HfG Offenbach)

which characteristics of the simulated space can be measured during goal-directed movement behavior in the test situation and what degree of realism is advisable for a given simulation with respect to the given sequence of interactions. The results also demonstrate that design modifications can be tested effectively in virtual reality. This has meant the development of important groundwork for subsequent research. Moreover, the project has generated large-scale research data that has yet to be fully evaluated, while developing and successfully implementing an interdisciplinary research approach.

It has been shown that eye-tracking in virtual reality allows us to measure with precision which objects are viewed, for how long, how often, and at which locations. The correlation of measurement data with interpretive-phenomenological interviews yields reliable results concerning the impact of design measures. In virtual reality, design elements such as lighting, surface quality, color, object positioning, and object form, along with spatial structure, can be varied and tested in targeted ways. A limitation of such simulations, it must be conceded, is that they are able to reproduce social interactions, imparted via avatars, only to a limited degree (they were not taken into account in the test set up). The limitations of the test capabilities are also evident when it comes to aesthetic effects: with the current state of technology, atmospheric impressions caused by bodily sensations in spatial situations are not attainable.

The test area was restricted to the navigation of a public mobility space, and hence to goal-directed action (with intentionally oriented attention). Foregrounded here, correspondingly, were the functional demands on design, on the ways in which information, object positioning, and spatial structure can be used to facilitate and improve orientation, and hence wayfinding. Subsequent research will go beyond functional demands to incorporate the emotional impact of design (for example, a sense of well-being or a subjective sense of security) with greater emphasis.[05]

The findings of the psychology of perception and cognition are of considerable interest for design research, allowing well-founded, quantitative evaluations of the influence of design decisions on perception and the assessment of spatial situations. At the same time, the formal-analytical model of product language represented a point of connection with the analytical approach of scene grammar. The rules of scene grammar, produced by abstracting from spatial interactions, as well as the operationalization of anchor objects, constituted an important foundation for the research project. This approach was extended through the integration of findings from architectural and design theory with regard to the investigation of spatial processes but will need to be illuminated in greater detail in the future, in particular with regard to their referential and offer functions (indications/affordances) and their symbolic meaning (product semantics). The methods of scene grammar are well suited to the investigation of wayfinding in mobility spaces and can be quite productively linked with the research methodology of design studies. This makes possible valid statements concerning the impact of individual design parameters. This does not replace the design process, the concrete design, but does provide designers with important references concerning the potential impact of a variety of design parameters, depending on the location's framework conditions and user intentions. Research carried out to date was able to determine that a systematic examination of design parameters is possible in virtual reality, even though the areas of investigation need to be differentiated further, and moreover examined with an eye toward their ecological validity.

Virtual reality simulations have a high application potential, and not just in interdisciplinary basic research. In the context of transportation infrastructure measures, they allow planners and designers to gather feedback from users during the initial planning stages, thereby qualifying the design. Moreover, they can be highly effective in communication terms, since they are able to convey the quality of the design with a high degree of credibility to clients, decision-makers, or the users; conversely, they can also be useful in avoiding planning mistakes. In this context, the degree of realism is of great significance, for it vouches for

the »credibility« of the design, for in the end, after all, the quality of the planning and design is essential. The results presented here represent a contribution to making human-centered design and planning possible in planning processes through the application of virtual reality technology.

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