IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 12, 2020, accepted September 15, 2020, date of publication September 23, 2020, date of current version October 5, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3025634

Spatial Perception of 3D CAD Model Dimensions and Affordances in Virtual Environments

FANIKA LUKAČEVIĆ[1], STANKO ŠKEC[1], MARIJA MAJDA PERIŠIĆ[1], NIKOLA HORVAT[1], AND MARIO ŠTORGA[1,2]

[1]Chair of Design and Product Development, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 10002 Zagreb, Croatia
[2]Department of Business Administration, Technology and Social Sciences, Luleå University of Technology, 97187 Luleå, Sweden

Corresponding author: Stanko Škec (stanko.skec@fsb.hr)

This work was supported by the Croatian Science Foundation: Team Adaptability for Innovation-Oriented Product Development–TAIDE under Project IP-2018-01-7269.

ABSTRACT Design understanding and needed level of the accompanying spatial skills that enable it depend on information input provided by a visual representation of a design solution. During product development, designers use models to visually represent a design solution. These visual representations can be mediated by various technologies (for example, an *immersive virtual reality* (IVR) technology or 2D user interfaces such as a monitor display), providing designers with different types of information. Capabilities of an IVR technology such as stereopsis, eye-height reference, spatial updating, and multimodal interaction, have shown a potential to mitigate the cognitive load and the need for highly developed spatial skills enabling design understanding. Nevertheless, specific design understanding aspects for which IVR technology may be beneficial over conventional 2D user interfaces are yet to be clarified. The conducted experiment aimed to explore differences in designers' spatial perception of spatial properties and relations (affordances) of a design solution in *virtual environments* (VEs). The design solution was presented by a 3D CAD model in *immersive virtual environment* (IVE) and *non-immersive virtual environment* (nIVE). IVE was mediated using the IVR technology (*head-mounted display*; HMD), while nIVE using the conventional 2D user interface (a monitor display, a mouse, and a keyboard). Results indicate that engineering students more accurately perceive spatial properties in the IVE than nIVE. Besides, it is suggested that the likelihood of making the correct judgment of the affordance is similar in both VEs.

INDEX TERMS Affordance, design understanding, spatial perception, spatial properties, virtual environment.

I. INTRODUCTION

Tailoring design for ergonomics (human factors) nowadays is a common practice for consumer, but also technically oriented industrial products [1]. Ergonomics (human factors) play a major role in product development by applying information about human characteristics and behaviour to the creation of objects, facilities, and environments that people use [1]. Aside from human factors such as physical characteristics, perception of possible actions that users can perform on and with a product (i.e. affordances) [2], [3] should be considered when designing for usability [4]. These elements should be considered from the very beginning of the development project and checked as a constitutive part of design reviews since efforts to implement changes in early phases of product development require significantly lower resources than in later ones [1], [5]. Nevertheless, an inspection of these elements of a design solution during product development can be a demanding task requiring a comprehensive understanding of a design solution. Design understanding (the ability to comprehend a design solution, acquire knowledge about and make design decisions upon it) is guided by visual perception of intrinsic (such as orientation and arrangement of parts, size, rotation, scaling) and extrinsic (for instance, location relative to other objects or a reference frame) spatial properties of these solutions and spatial relations among them [6]. Accompanying cognitive abilities enable spatial reasoning needed for an understanding of a design solution [7], [8]. As a result, these abilities are essential for designers when performing design activities [9], [10]. They are often referred to as spatial abilities or skills and divided into three basic types, namely spatial perception, mental rotation, and spatial visualization [9]. Design understanding and needed level

The associate editor coordinating the review of this manuscript and approving it for publication was Francisco J. Garcia-Penalvo.

of underlying spatial abilities depend on information input provided by a visual representation of a design solution [6]. During product development, designers use various representations, such as 2D engineering drawings, 3D CAD models and mock-ups or physical prototypes to visually present a design solution [11], [12]. These visual representations can be mediated by various technologies, such as conventional 2D user interface (a monitor display, a keyboard, and a mouse) or 3D user interfaces (an *immersive virtual reality*; IVR). It has been argued that designers' understanding of a design solution differs depending on user interfaces in regard to the type of information that can be extracted from a specific mediated representation [13]. Moreover, studies often suggest a mutually dependent relationship between the effectiveness of the employment of user interfaces and spatial ability levels of their users [9], [14]–[16].

The advent of a new generation of IVR technology in recent years prompted an enlarging number of the studies exploring its effect on design activities across architecture, engineering, and construction (AEC) disciplines. Several recent examples within engineering design domain are provided by de Casenave and Lugo [11], Horvat *et al.* [17], Wolfartsberger [18], Lukačević [19]. Nevertheless, design review activities and underlying design understanding aspects for which IVR technology may be beneficial over conventional user interfaces are yet to be clarified. The aspect of a design understanding explored in this study is a spatial perception of spatial properties and relations (affordances) of a design solution presented by a 3D CAD model in a *virtual environment* (VE). More specifically, the observed spatial properties are the overall dimensions of a reviewed design solution, while affordance refers to the possibility of taking a preferable position related to the design solution presented in a VE. The VE is defined as a visually represented environment that is stored in the computer and experienced by a user [20]. The conducted study aims to explore differences in designers' spatial perception of spatial properties and affordances in two VEs of different immersion levels. An *immersive virtual environment* (IVE) was mediated using IVR technology (*head mounted display*; HMD), while *non-immersive virtual environment* (nIVE) using the conventional 2D user interface (a monitor display, a mouse, and a keyboard).

The remained of the paper is organized as follows. A description of the research background and an overview of the related studies of spatial perception in the AEC domains are provided in section II. The methodology of the study is described in section III. Results are reported in section IV. This is followed by a discussion of results in section V. Finally, drawn conclusions and outlines for further work are presented in section VI.

II. RESEARCH BACKGROUND AND RELATED WORK

Section II-A introduces a relationship between visual representations, virtual environments, and spatial abilities as a basis of the theoretical background of the presented work. Further, section II-B presents an overview of the commonly used measures of spatial perception. This is followed by an overview of the reported empirical research on spatial perception in the AEC domains within section II-C.

A. SPATIAL ABILITY AND VIRTUAL ENVIRONMENTS

Spatial information contained in visual representations concerns spatial properties of visual stimuli (presented objects and environments) [21]. This information includes properties of the objects and environments (for example size, shape, and scale), and relations among elements of the objects themselves and other objects in the environment (some examples are distance, direction, orientation, and location) [7], [21]. To perceive the spatial information, the mental representation of a three-dimensional model of its spatial layout has to be made [22]. The three-dimensional mental model is created by the perceptual system using visual cues (such as binocular disparity and stereopsis) and internalized assumptions about the environment based on past experiences [23].

It has been argued that mental imagery depends on the type of visual representation (for instance drawing or 3D CAD model) and the visualization media (such as conventional 2D user interface or IVR technology) used to present it [24]. In addition, Hegarty *et al.* [25] suggest that processing of spatial information depends on the scale of an environment relative to the user's body. Considering a relationship between presented VE and users' body, visual representations are often divided into allocentric (objective) and egocentric (body-relative) [7], [26]. Conventional monitor display mediates an allocentric representation of a VE; it is independent of the user and does not refer to the user or any part of its body [26]. Furthermore, the two-dimensional nature of the conventional monitor display is its limitation [27], which is diminishing fidelity of representation and efficiency of its usage [28]. On the other hand, IVR allows a user to interact with a 3D CAD model inside a VE from the first-person view [29] using a stereoscopic display [30] and providing a multimodal interaction [31]. So, IVR mediates an egocentric representation of a VE, which is often referred to as an IVE; one in which a user is perceptually surrounded by the VE [20].

Taking into account the abovementioned distinction between visual representations (egocentric and allocentric), spatial abilities (skills) are classified into four basic categories [7]. Namely, an intrinsic-static, an intrinsic-dynamic, an extrinsic-static, and an extrinsic-dynamic spatial skill [7]. Hence, reference frames of users' body (in relation to a visual representation) seem to affect spatial skills. For example, Guzsvinecz *et al.* [32] reported on differences in spatial skill levels when they are assessed using conventional user interfaces and IVR technology. It is possible that different levels of spatial skills are needed for an understanding of a design presented by egocentric and allocentric visual representations [8]. Similarly to the spatial skills, tasks through which spatial perception is assessed are divided into extrinsic and intrinsic [7]. Extrinsic tasks (such as judgment and estimation of a dimension size or a distance) are usually related to perceiving spatial properties without a reference to the user's body. In contrast, intrinsic tasks (such as the perception of affordances) require a mapping between the user's body and the object or the environment in which it is placed.

B. STUDIES OF SPATIAL PERCEPTION IN VEs WITHIN THE AEC DOMAINS

Across domains, the spatial perception has been assessed using various measures focused on different spatial properties (for instance, dimensions or distances) and affordances (such as body-scaled affordances) of visual stimuli (a VE) [33]. Spatial properties and affordances are characteristics of an environment and object(s) within it. Thus, they have been used as a proxy which enables assessment of spatial perception. It is common to use those spatial perception measures which are appropriate for the specific topic of interest within the certain domain. For example, dimensions when analyzing 3D CAD models [34] or body-scaled affordances when detecting the shortcomings of a room layout [35]. For reporting judgments or estimations to assess spatial perception when performing respective tasks in the experiments, extrinsic and intrinsic metrics have been employed. Sections II-B-1 and II-B-2 provide an overview of related studies within the AEC domains, with references to the outlined measures of spatial perception and used metrics.

1) STUDIES OF PERCEPTION OF SPATIAL PROPERTIES

When investigating spatial perception in VEs, scholars in the AEC domains often focus on spatial properties such as dimensions of objects or distances between several objects. For example, Gîrbacia *et al.* [34] conducted an experiment with the aim of analyzing depth perception of reviewed 3D CAD models (assembled from parallelepiped parts) in IVE and nIVE. Depth estimation was verbal, expressed in extrinsic metrics (centimeters) and based on comparison with the known size of the virtual table on which 3D CAD models were positioned. They concluded that the accuracy of the estimation depends on the actual value of the assessed dimension; in the IVE-based review, accuracy was higher for large values of the depth. Another finding was that participants in the IVE overestimated the depth value for all the models that were used in the experiment. The comparative study done by Horvat *et al.* [17] assessed engineering students' spatial perception of 3D CAD models of products with different levels of complexity while reviewing them using IVR technology and conventional 2D user interface. Participants were asked to verbally estimate the size of the models' dimensions. Results showed that the estimation of the model dimensions was enhanced when IVR was used. Furthermore, in the same study, scholars also reported that differences between a desktop interface and IVR for reviewing models were more evident for 3D CAD models of higher complexity levels [17]. In architectural design, Paes *et al.* [24] conducted an experiment that included asking the participants to identify correct values of spatial properties (such as dimensions, proportions, and apertures) of an entrance hall of the building presented in IVE, nIVE, and physical environment. Participants were provided with the several possible values of the examined dimensions and distances to choose from. Findings of the study indicated that IVE-based design review led to the enhanced understanding of the spatial arrangement of the virtual model. The study conducted by Satter and Buttler [36] measured spatial perception of participants (15 novices and 15 experienced designers) through the action-based test of locating the object (a 3D icon) in an unfamiliar environment. The analyzed measure was the distance (in millimeters) between the perceived and actual location of the object. The study results showed an improvement of 695% (based on the correctness of the estimated distance) in spatial perception when IVE was used in comparison to the usage of nIVE. In another study, Schnabel and Kvan [37] explored participants' spatial perception in VEs through tasks in which they were obliged to construct models of a cuboidal spatial assembly based on the analysis of the spatial relationships between its elements. Study results reported that reviews in IVE yielded more detailed models, based on which it was concluded that IVE provided participants' enhanced comprehension of dimension ratio and design.

2) STUDIES OF PERCEPTION OF BODY-SCALED AFFORDANCES

Affordances are defined as relations between spatial properties of objects, multiple objects or objects and an environment in which they are placed [2]. Particular subcategory of the abovementioned relationships are body-scaled affordances, defined by the fit between dimensions of a human body and other objects or environments [22]. It is perceived as a possibility for interaction (such as pass-ability or reach-ability) provided by the environment or objects inside it for a human with specific dimensions and movement capabilities [2], [22]. Studies that include perception of affordances in the AEC domains often rely on qualitative analysis, while the accuracy of participants' answers usually is not reported. Perception of body-scaled affordances using IVR technology in product development has mostly been explored through the perception of ergonomics (human factors) in the context of requirements definition or validation. For example, Berg and Vance [38] recognized that, in an industrial environment, IVR has been used by ergonomic engineers to establish design criteria during the setup of a design specification. For example, for a definition of a maximum allowable assembly force, the position of the door handle, accessibility of the filter panel while avoiding the guardrails to reduce customer maintenance costs, or an evaluation of the best control arrangement of a vehicle interior. Thus, it can be noticed that IVR has been used for consideration of human factors for various stakeholders that will be in contact with the product during different stages of its lifecycle. Furthermore, Horvat *et al.* [17], in the comparative study mentioned in the previous section, also assessed engineering students' perception of fit of UIEs (such as grasp-ability of a handle ball) in the context of a design review. Their conclusions suggest that perception of fit of UIEs was enhanced for participants that conducted a design review in IVE. As well, their results suggested an enhanced spatial perception of models at higher complexity levels. In construction, body-scaled affordances often refer to the layout of the elements inside a building or a room. For example, results of the experimental part of the study conducted by Dunston *et al.* [35] revealed that IVR led to the detection of shortcomings in hospital room layout concerning relationships between spatial properties, such as insufficient clearances between furniture elements or over-dimensioned elements. Within the same domain, Bassanino *et al.* [39] conducted design review case study concerned with a redesign of the bathroom for disabled people during which IVR allowed a wheelchair user to test the accessibility of the bathroom presented by the virtual mock-up.

C. RESEARCH GAPS

Investigation of spatial perception has primarily been a research interest of scholars in a domain of psychology. Studies in this domain have often been conducted without a reference to IVR technology (for example, [40]) or IVR has been used as an experimental tool, not a research variable [7]. As a result, the majority of the studies of spatial perception are out of the context of design activities and do not research differences in spatial perception among VEs.

In the engineering domain, studies related to spatial perception in VEs have been conducted with different goals (such as usage of IVEs for requirements validation [38], an inspection of a room layout [35], or an analysis of depth perception of reviewed 3D CAD models [34]) and employing various methods (for example, verbal estimations reported in extrinsic metrics [17], [34], identification of correct values of spatial properties [24] or action-based tests of locating an object in a VE [36]). Due to these differences among the studies, the findings they report are anchored to the context of their specific cases. Consequently, these studies do not imply findings relevant in the general engineering design context.

Further, it is argued that the studies of spatial perception in the engineering domain do not consider insights from the domain of psychology when selecting the measures and tasks. The majority of the reviewed studies uses only one measure to assess spatial perception (either spatial properties or affordances). Besides, these studies employ different technologies, design solutions, and samples (considering the number of participants and their backgrounds). Consequently, the findings reported in the previous studies cannot be directly compared. In addition, they are often not comparative studies that include a detailed statistical elaboration of results. Rather, they report on qualitative findings employing only one visualization technology. On the other hand, studies that report empirical results often include simple technical systems or solid figures (such as a cube or a cube assembly), which do not represent realistic engineering design cases.

The conducted literature review has not revealed studies that assess, quantitatively analyze, and compare designers' spatial perception of design solution's spatial properties and affordances in VEs during engineering design activities. Hence, a need has been recognized for the study exploring differences between IVE and nIVE in designers' spatial perceptions of spatial information which is contextualized for the activities related to engineering design. To assure a methodological rigour, it is argued that the study should follow suggestions and methods from the domain of psychology.

With an intention to overcome the recognized literature limitations, the experiment was performed with engineering students in the context of the tasks specific for activities within a design review. The presented work aims to contribute to a better understanding of differences in spatial perception of mediated visual representations of design solutions among IVE and nIVE Based on the reviewed literature, it is argued that different tasks (extrinsic and intrinsic) should be employed when assessing spatial perception during a review of a design solution in a VE. Spatial perception of engineering design students was assessed through the extrinsic task - verbal estimations of spatial properties (dimension sizes) and the intrinsic task - judgments of spatial relations (body-scaled affordance; perception of fit of UIEs). The presented study tends to answer two research questions:

1) Are designers' spatial perceptions of 3D CAD model dimensions different in the IVE and the nIVE?
2) Are designers' spatial perceptions of body-scaled affordances different in the IVE and the nIVE?

Reviewed literature often reported on properties of a human perceptual system (such as first-person view, eye-height reference, spatial updating, stereopsis, and multimodal interaction) having a great impact on spatial perception. These properties also characterize an IVR, but not a conventional 2D user interface. Consequently, the IVR mediates an egocentric, while the conventional 2D user interface an allocentric visual representations. A reference frame of the users' body, which is dissimilar for the egocentric and the allocentric visual representations, tends to be important for design understanding and underlying spatial skills (such as spatial perception). Hence, it is hypothesized that designers' spatial perceptions of 3D CAD model dimensions (hypothesis 1) and body-scaled affordances (hypothesis 2) differ in IVE and nIVE.

III. RESEARCH METHODOLOGY

The empirical part of the presented research has been conducted as a quantitative and comparative experimental study that employs a descriptive and inferential statistical testing. The design of the study is based on principles and methods described by Robinson [41] and guided by published experimental studies concerned with spatial perception as one aspect of a design understanding in engineering domain (for instance, [6], [24], [34], [42], [43]). In addition, studies from the domain of psychology were used as a basis for a definition of tasks and spatial perception measures (some examples are [20], [40]). Building on the abovementioned studies, the presented work explores differences in designers' spatial perceptions when assessed in both the intrinsic and extrinsic task in the IVE and the nIVE. The conducted study further explores differences in relationships between several types of spatial skills and spatial perception among the IVE and the nIVE for these tasks.

The study was conducted in eight steps. Firstly, experimental variables were developed, and their measures were determined. Secondly, a design solution to be reviewed was selected, and design review tasks and questions were defined. Thirdly, the experimental setup was defined, and pilot experiments were conducted. Next, a full experimental procedure was defined. After that, the experiments with 40 participants were conducted. This was followed by an analysis of the collected data. These steps are further explained in the remainder of this section.

A. EXPERIMENTAL VARIABLES AND THEIR MEASURES

Development of experimental variables and their measures was guided by the research literature on visual representations of design solutions, together with empirical studies of spatial perception using different visual representations (see section II). Spatial perception of spatial properties of the 3D CAD model presented in a VE and its affordances, as an aspect of a design understanding, was a dependent variable in the conducted experiment. It was measured through two tasks concerned with an estimation of the size of the overall dimensions of the scooter (extrinsic task) and judgment of the scooter's driving position affordance (intrinsic task). Dimensions as spatial properties and a body-scaled affordance were selected as measures since their relevance in the engineering design has been confirmed by the previous related studies within the domain (for example, [24], [34], [36], [44]). The tasks are further described in section III-B. These tasks were followed by confidence judgments, reflecting the participants' beliefs in the accuracy of their answer concerning the particular task [45]. Confidence (C_{rm}) was judged on the open-ended confidence rating scale [45] from 0% (absolutely unsure) to 100% (absolutely sure).

It has been argued that design understanding depends on two factors: a visual representation of a design solution, and prior knowledge and experience of design reviewers [6]. The reviewed design solution was visually presented by 3D CAD model in two VEs of different immersion level. In such a way, a VE in which the design solution was presented is an independent variable. Standardized *Presence Questionnaire* (PQ) [31] was employed for measuring participants' experienced presence in VEs to compare these VEs and clarify levels of immersion they provide. The experienced presence is based on the interpretation of information gathered through the stimulation of senses [27]. Higher presence has often been reported in VEs mediated by IVR and lower presence in ones mediated by conventional 2D user interfaces (for example, see [6]). Because of this (usually significant) difference, it is common to refer to the VE mediated by IVR as IVE and to the one mediated by conventional 2D user interfaces as nIVE. Nevertheless, although not usual, high presence can be experienced in VEs mediated by conventional 2D user interfaces and low presence in VEs mediated by IVR [6], [46]. Self-reporting using questionnaires is the most common way of measuring presence experienced in a VE [47]. Employed PQ allowed a comparison of VEs based on four subscales embracing both technological and human factors and defining an overall experienced presence. Namely, *involvement*, *immersion*, *sensory fidelity*, and *interface quality*.

Previous research studies have often measured the spatial ability of participants employing different surveys or tests prior to the experimental tasks. For example, de Casenave and Lugo [11] used the *Spatial Cognition Survey*, while Calderon-Hernandez *et al.* [48] employed the *Purdue Spatial Visualization Test: Visualisation of Rotations*. Participants' spatial ability was measured as an intrinsic-dynamic spatial skill of mental rotation in the conducted experiment. This spatial skill presents the second independent variable. It was measured through the standardized *Mental Rotations Test* (MRT) [49]. Based on their MRT scores, the participants were divided into two groups. One group reviewed the design solution in the IVE, while the other one in the nIVE to bypass a potential bias of previously conducted review.

Besides through the MRT, information about participants' prior experience was gathered employing the questionnaire. It contained 25 questions divided into three sections, namely, personal and demographic information (such as gender, nationality, and height), prior experience in designing and using CAD tools (concerning IVR technology, 3D CAD software, DRs, etc.), and contextual experience (for example, experience using three-wheeled vehicles). Results of several studies indicated the relationship between aspects of prior knowledge and experience and design understanding. For example, Paes, Arantes and Irizarry [24] and Calderon-Hernandez *et al.* [48] reported on the significant relationship between design understanding and age, educational level, and years of experience. Nevertheless, these sets of information are herein used to support a discussion, not to examine their effect on spatial perception. Such an analysis is beyond the scope of this paper, and it is noted as the suggestion for further work.

B. REVIEWED DESIGN SOLUTION

The selected design solution for a review was a lightweight foldable mobility scooter; a technical system of the third level of complexity – device which consists of sub-assemblies and parts that perform a closed function [50]. The selected scooter differs from the design solutions or objects commonly investigated in related studies of spatial perception (see section II). As it is argued in section II, related studies in the engineering domain often involve solids or simple technical systems. Similarly, measuring the spatial skills of individuals in psychological studies usually include tests that involve small manipulable objects such as blocks or sheets of paper [25]. In addition, experiments related to a perception of affordances often incorporate systems such as sliding doors or constructions consisting of two distanced poles to investigate pass-ability between them (for example, [44], [51]). Hence, the selected scooter, as a consumer product with various UIEs, enables an appropriate proxy of typical design review activities in engineering projects.

C. EXPERIMENTAL SETUP AND PILOT EXPERIMENTS

A design review in the nIVE was conducted using the conventional technology setup. It encompassed a high-performance computer, a 24″ monitor screen, and interaction devices (a computer mouse and a keyboard). The resolution of the monitors was 1920 × 1080 pixels with the refresh rate of 60 Hz. Siemens NX® with incorporated tools was used as a software package to review the scooter in the nIVE. Participants reviewed the scooter in the IVE using the HMD IVR system HTC Vive Pro® and associated 3D controllers to review the scooter in the IVE. System display consisted of Dual AMOLED 3.5″ diagonal with the resolution of 1440 × 1600 pixels, the refresh rate of 90 Hz, and 110° field of vision. Model of the scooter was presented in the VRED Professional® 3D CAD package. Basic navigation through the 1.9m × 2m large virtual room was enabled employing 3D controllers. On top of that, participants were provided with tools for sectioning, rotating, and measuring (see Figure 1), which were enabled by the VRED *OpenVR Scripts*.

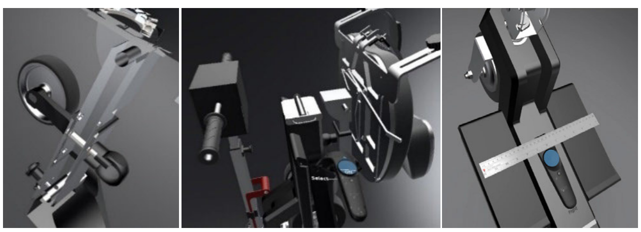

FIGURE 1. IVE with associated tools for sectioning, rotating, and measuring.

Pre-study pilot experiments were conducted with five participants. They enabled testing of the equipment, validation of the experimental protocol, and determination of a duration of each step of the experiment. Based on insights gathered through these pre-study pilot experiments, the full experimental procedure was defined, as it is explained in the following section.

D. EXPERIMENTAL PROCEDURE

The experimental procedure consisted of eight steps shown in Figure 2. Each participant completed all the steps of the experiment individually. Approximate duration of the experiment was 90 minutes. In the first step, participants were introduced to the experimental procedure. Secondly, the participants were asked to solve the MRT. Participants reviewed the scooter either in the IVE or nIVE. The division in two groups was based on the MRT scores, as it is described in section IV-C. Further, design review tutorial was shown to the participants. It contained explanations of the main objectives and the proposed procedure of a design review. This was illustrated with two examples. In the next step, participants were asked to complete the questionnaire on their prior experience. This step was followed by instructions on how to conduct tasks and answer questions; participants were asked to provide their answers by saying them aloud while performing a design review. In step 6, the participants were introduced to the equipment. Firstly, they were exposed to a video recording showing available tools and their usage in a VE. Afterwards, participants were asked to conduct four exemplary tasks (they were the same in both VEs) to become familiar with VEs and tools. The next step was conducting the design review of the scooter through extrinsic and intrinsic tasks described below and answering questions about confidence judgment. In the last step, participants were obliged to complete the PQ.

1) EXTRINSIC TASKS (ESTIMATIONS OF SPATIAL PROPERTIES)

Extrinsic tasks examined estimations of spatial properties (dimensions and distance sizes) of two objects, namely, the scooter and the participant's body. In particular, participants were asked to verbally estimate the sizes of the overall dimensions (height, length, width) of the folded scooter and a horizontal distance between their heel and back. They were obliged to verbally report their estimates using extrinsic metrics (millimeters). The estimated dimensions and distance are depicted in Figure 3.

In the first extrinsic task, participants were asked to verbally estimate the size of overall dimensions of the scooter in the folded mode. Participants did not know the actual values of these scooter's dimensions prior to this task, and they were instructed not to use the measuring tool. Figure 4 depicts participants conducting this task in VEs.

The second extrinsic task was an auxiliary task, conducted to support the analysis and discussion of the intrinsic task. The participants were instructed to sit on a chair whose seat was set on the height of 550 mm from the ground level (as is the seat of the scooter presented in a VE) and lean their back on the backrest. Second, they put their body in the preferable driving position considering the horizontal distance between their heel and back. Finally, participants verbally estimated the horizontal distance between their heel and back ($D_{\mathrm{H-B}}$) in that position. The examiner measured the actual size of the distance to enable an analysis of the accuracy of participants' estimates. Estimations of the horizontal distance $D_{\mathrm{H-B}}$ in the real world (RW) and the nIVE are illustrated in Figure 5.

2) INTRINSIC TASK (JUDGMENT OF A BODY-SCALED AFFORDANCE)

An intrinsic task presented below examined the judgment of a driving position affordance. Participants were asked to

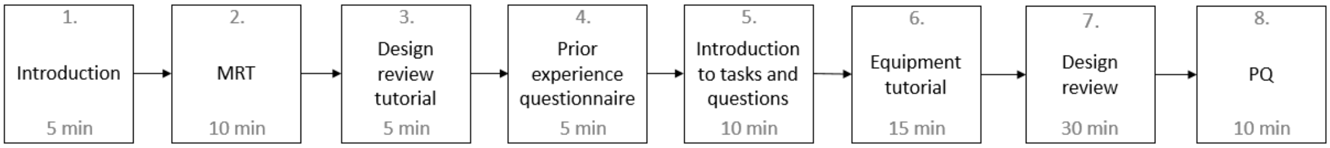

FIGURE 2. Experimental procedure.

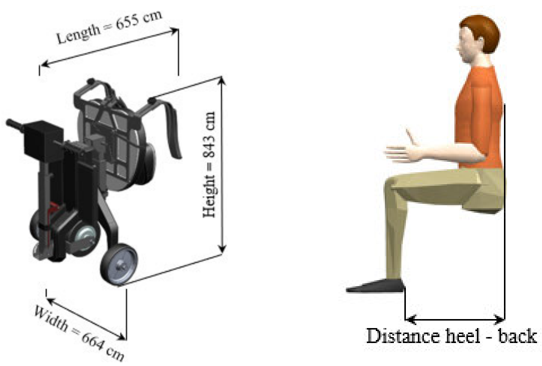

FIGURE 3. Spatial properties: the overall dimensions (left), the distance between the heel and back (right).

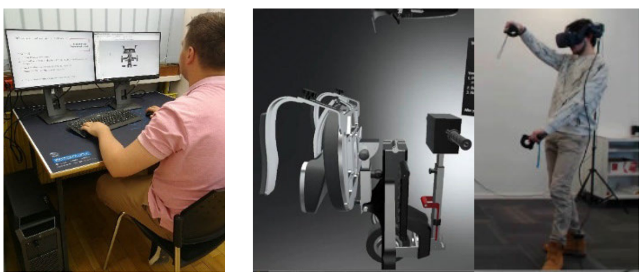

FIGURE 4. Estimation of the overall dimensions in the nIVE (left) and the IVE (right).

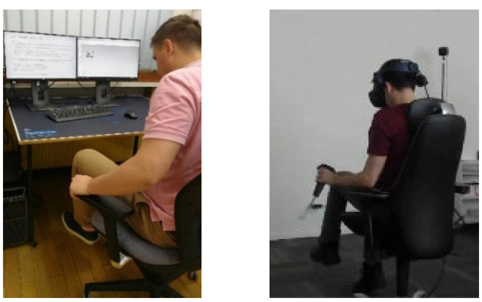

FIGURE 5. Estimation of the horizontal distance D_{H-B} in the real world (left) and the IVE (right).

determine the possibility of being in the preferable driving position on the scooter presented in a VE. In other words, they were asked to judge if the presented scooter affords the preferred driving position. The driving position affordance referred to the position in which participants can at the same time sit in the seat (set on the height of 550 mm), lean their back on the seat backrest and put the most of their feet on the feet holders (distanced for 520 mm from the seat back and long 280 mm). These dimensions are denoted in Figure 6.

FIGURE 6. Dimensions of the scooter in the driving mode.

Participants were provided with values of actual dimensions of the scooter (they were written on the screen). A chair with a backrest and a seat set on the height of 550 mm measured from the ground level (same as the seat of the scooter presented in the virtual environment) was available to the participants during the task performance. Figure 7 shows the participants conducting this task in IVE and nIVE.

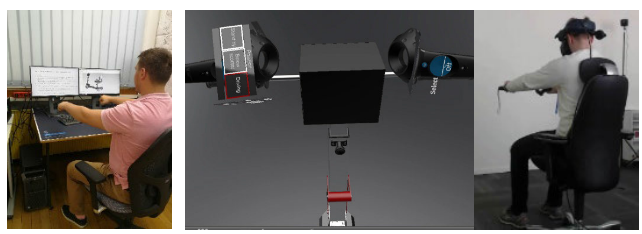

FIGURE 7. The judgment of the driving position affordance in the nIVE (left) and the IVE (right).

E. CONDUCTING THE EXPERIMENTS

In total, 40 graduate and undergraduate engineering students participated in the study. The requirement for participating was an engineering field of studies, while the year of a study, specialization, prior design experience or experience with 3D CAD software and IVR technology were not predefined.

F. ANALYSIS OF COLLECTED DATA

Statistical analysis of gathered data was conducted using the R language. Descriptive statistics enabled a calculation

TABLE 1. Prior experience of participants.

Year of study [number]	1	2	3	4	5	
Number of participants	1	4	14	15	6	
CAD skills [level]	None	Limited	Basic	Intermediate	Advanced	
Number of participants	3	3	13	17	4	
CAD experience [time]	None	1 month	1 year	3 years	5 or more	
Number of participants	2	6	10	16	6	
DR experience [number of DRs]	None	1 - 3	4 - 6	7 - 9	≥10	
Number of participants	21	7	5	2	5	
IVE experience [minutes]	None	>5	5 - 15	15 - 60	150 - 210	780
Number of participants	23	3	6	4	3	1

of central tendencies (mean value) and variability (standard deviation), while inferential tests allowed an analysis of a difference in results between experimental variables. Procedure for a comparison of two variables was: (1) *Shapiro-Wilk test*, (2) *Levene test*, (3) *t-test* or *Wilcoxon rank-sum test* (if normality assumption was violated, as tested by *Shapiro-Wilk test*; $p < 0.05$) or *Welch's t-test* (if normality assumption was met, but the assumption of the equality of variances was violated, as tested by *Levene test*; $p < 0.05$).

IV. RESULTS

An overview of participants' demographics and prior experience is offered in section IV-A. Next, VEs are compared employing descriptive statistics and inferential tests to see if the scores on the PQ's subscales and participants' overall experienced presence were significantly different. In section IV-C, results of the MRT are provided. After that, the effect of a VE on the accuracy of the estimations of the scooter's dimensions (extrinsic tasks; section IV-D) and judgment of a driving position affordance (intrinsic task; section IV-E) is analyzed using descriptive statistics, inferential tests, and regression analysis. In addition, the effects of engineering students' spatial perceptions of anthropometric measurements of their body on their spatial perceptions of body-scaled affordances in VEs were analyzed employing the descriptive statistics and inferential test. These were additionally used to investigate effects of the intrinsic-dynamic spatial skill of mental rotation, immersion, and confidence on spatial perceptions of body-scaled affordances in VEs.

A. DEMOGRAPHICS AND PRIOR EXPERIENCE)

Altogether, 33 male and 7 female participants took part in the conducted experiment. The average age was 22, with a range from 19 to 31 years. Participants were engineering students in four different fields. Namely, engineering design ($n = 16$), industrial design ($n = 15$), materials engineering ($n = 7$), and sustainable energy engineering ($n = 2$). The educational level of participants (year of the study), their CAD skills, CAD experience, design review (DR) experience (number of conducted DRs) and IVE experience (minutes spent in the IVE) are provided in Table 1.

B. PRESENCE QUESTIONNAIRE (PQ)

Analysis of participants' responses showed that the VE mediated by the IVR technology scored higher on each subscale of the PQ; involvement, immersion, sensory fidelity, and interface quality (as it is presented in Table 2). Because of the assumptions on the normality of distribution and homogeneity of variances, differences in VEs were analyzed employing *t-test* for involvement and interface quality, *Welch's t-test* for immersion, and *Wilcoxon's rank-sum test* for sensory fidelity. The differences between VEs were significant only for involvement and immersion. These results confirmed that the VE used in the study and mediated by the IVR was significantly more immersive than one mediated by the conventional 2D user interface. Hence, the VE mediated by the IVR can be referred to as the IVE and one mediated by the conventional 2D user interface as the nIVE. Analysis of aggregated responses (for all the four subscales) employing *t-test* revealed that the VE mediated by the IVR technology achieved significantly higher PQ scores than one mediated by the conventional 2D user interface ($p = 9.633 \cdot 10\text{-}5$).

TABLE 2. Presence questionnaire subscales.

Subscale	IVE	nIVE	p
Involvement	67 ± 9.7	54 ± 10	0.0002954***
Immersion	45 ± 7	40 ± 4.3	0.0004471***
Sensory fidelity	12 ± 1.7	11 ± 3.2	0.3508
Interface quality	15 ± 4.5	13 ± 2.7	0.4155
Total	140.2 ± 15.5	115.8 ± 17.1	$9.633 \cdot 10^{-5}$***

Form of the values presented in the table is: Mean value ± Standard deviation.

*p < 0.1; **p < 0.05; ***p < 0.01

C. MENTAL ROTATIONS TEST (MRT)

As mentioned in section III, participants were divided into two groups (one reviewed the scooter in IVE, while another in nIVE) based on their MRT scores. The division was conducted in a way to maintain the approximately equal distributions of MRT scores in both VEs. Distributions are presented in Figure 8. The mean MRT score of all the participants was 13.4 ± 4.6, for the group that conducted the review in the IVE was 12.7 ± 4.5, while for the nIVE group 14.1 ± 4.7.

D. ESTIMATIONS OF SPATIAL PROPERTIES (EXTRINSIC TASK)

The analysis is based on the mean values and standard deviations of relative errors that participants made in their

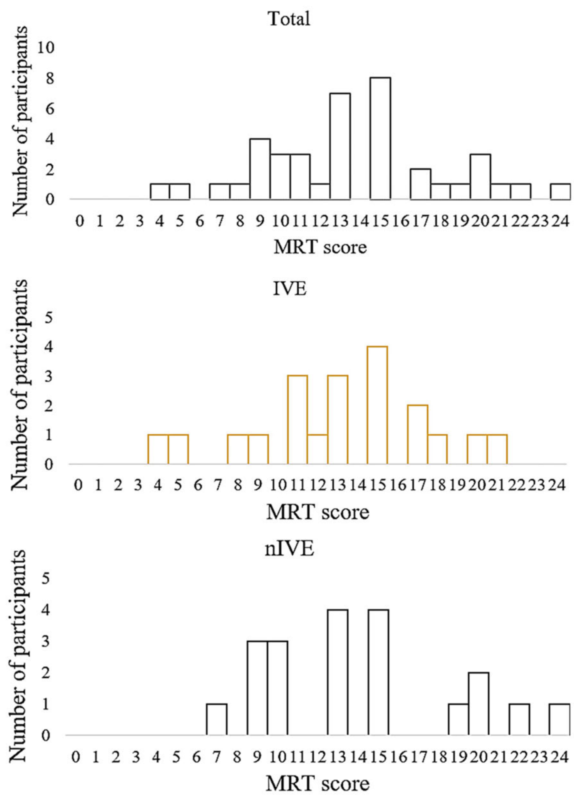

FIGURE 8. Distribution of MRT scores: all participants (top), IVE participants (middle), nIVE participants (bottom).

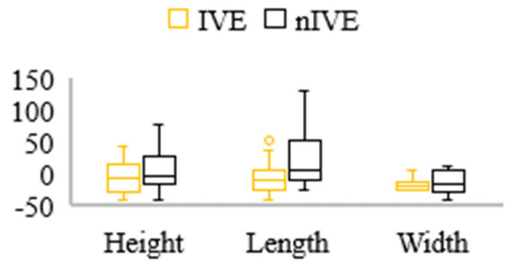

FIGURE 9. Boxplots: Errors in the estimation of the overall dimensions.

estimation of dimensions and distance sizes. They are presented in the tables below. The relative estimation error (E) is calculated as a ratio of two values; a difference between an estimated (D_E) and an actual (D) size of a dimension/distance ($D_E - D$) and actual size of a dimension/distance:

$$E = (D_E - D)/D. \tag{1}$$

If the value of an E is positive, the participant overestimated the dimension/distance size, while the negative value of the E means that the participant underestimated the size of a dimension/distance.

1) ESTIMATIONS OF THE OVERALL DIMENSIONS OF THE FOLDED SCOOTER

The majority of the participants that reviewed the scooter in the IVE underestimated sizes of all three dimensions (as it can be noticed from Table 3). On the other hand, there were no notable differences in over- and underestimates in the nIVE. In fact, only for the length this number was different, with the overestimates of the length size being prevalent in the nIVE. The highest E was obtained for the length of the scooter when estimated in the nIVE. Boxplots in Figure 9 present the distributions of E for these three dimensions and their differences in IVE and nIVE.

The *Wilcoxon's rank-sum test* showed that the differences in the Es in IVE and nIVE were statistically significant for length ($p = 0.04555$) and width ($p = 0.02694$). With a statistical confidence level of 95%, the Es of the length were smaller in the IVE. For the width, differences between VEs were significant due to distinction in the number of over- and underestimates, not in values of Es. *T-test* showed that the difference between VEs was not statistically significant for height ($p = 0.1116$).

Friedman's rank-sum test was employed to test for the differences among Es of the height, length, and width within each VE. In such a way, it was examined how an individual's Es differ along dimensions. The results showed that these differences were statistically significant both in the IVE ($X2(2) = 12.5$, $p = 0.00189$) and the nIVE ($X2(2) = 12.7$, $p = 0.00173$). *Pairwise Wilcoxon signed-rank test* revealed statistically significant differences between Es of height, length, and width. In the IVE, this difference was statistically significant between height and width ($p = 0.008$), and length and width ($p = 0.000260$). In the nIVE, difference was also statistically significant between height and width ($p = 0.024$), and length and width ($p = 0.003$). These results indicate that, irrespective of the VE employed, a participant's Es related to the height, length, and width are likely to differ. Namely, in IVE, a participant's E in estimating height and length is usually lower than in estimating width. On the contrary, participant's E for height and length in nIVE tend to be higher than for width.

A difference between IVEs was analyzed considering the order in which dimensions were estimated. It can be noticed from Table 4 that the Es may depend on the order of estimations. It seems that the E decreases in nIVE after the first estimation, while in the IVE it first decreases and then enlarges. *Friedman's rank-sum test* was employed to test for the differences among Es of the first, the second, and the third estimated dimensions in each VE. In this way, it was examined how an individual's Es differ among the estimated dimensions depending on their order. The results showed that the differences were statistically insignificant both in the IVE ($X2(2) = 2.77$, $p = 0.250$) and the nIVE ($X2(2) = 0.718$, $p = 0.698$). These results offer no evidence that a participant's first, second and third Es follow a specific pattern.

Differences between the IVE and nIVE in the Es were analyzed separately for the first, second, and third estimated dimension. Boxplots in Figure 10 present the error

TABLE 3. Estimation errors of the overall dimensions.

		Nº	*E* of height	Nº	*E* of length	Nº	E of width
IVE	Total	20	16.1% ± 12.6%	20	15.6% ± 13.3%**	20	18.8% ± 9.4%**
	Overestimated	6	21% ± 10.8%	8	10.75% ± 16.1%	2	23.3% ± 7.5%
	Underestimated	14	18.6% ± 13.3%	12	17.7% ± 10.9%	18	22.1% ± 8.8%
nIVE	Total	20	22% ± 23.3%	20	27.0% ± 29.9%**	20	19.2% ± 15.4%**
	Overestimated	10	37.6% ± 28%	12	45.3% ± 33.4%	10	21.6% ± 17.4%
	Underestimated	10	15.1% ± 11.2%	8	13.1% ± 8.7%	10	24.5% ± 12.9%

Form of the values presented in the table is: Mean value ± Standard deviation.
*p < 0.1; **p < 0.05; ***p < 0.01

TABLE 4. Comparison of the *E*s considering the estimation order.

	E of the first dimension	*E* of the second dimension	*E* of the third dimension
IVE	20.4% ± 9.9%**	16.7% ± 12.7%*	24.2% ± 12.2%***
nIVE	29.2% ± 20.8%**	25% ± 18.2%*	25% ± 30.7%***
Aggregated	24.8% ± 16.9%	20.8% ± 16.2%	24.6% ± 23.4%

Form of the values presented in the table is: Mean value ± Standard deviation.
*p < 0.1; **p < 0.05; ***p < 0.01

FIGURE 10. Boxplots: Errors in the estimation of the overall dimensions considering the estimation order.

distributions for respective dimensions in IVE and nIVE. The *Welch's t-test* showed that the differences in the *E*s in the IVE and the nIVE were statistically significant for the first estimated dimensions ($p = 0.01425$). These differences were statistically significant for the second estimated dimensions only at the confidence level of 90% ($p = 0.09324$). The *Wilcoxon's rank-sum test* showed that the difference was statistically significant for the third estimated dimensions ($p = 0.002702$).

Results of the confidence judgment showed that participants were more confident in their overall dimension estimates in the IVE (67% ± 12.5%) than in the nIVE (43.8% ± 18%). The *Wilcoxon's rank-sum test* confirmed the significance of confidence differences between IVE and nIVE ($p = 0.0002776$).

Finally, the relationship between the MRT scores and spatial perceptions of the overall dimensions was investigated employing the regression analysis. Linear regression was used to analyze a relationship among the *E*s of the overall dimensions and the MRT scores. The results of the regression analysis showed that the models were insignificant (see Table 5), implying that there is no evident

TABLE 5. Linear regression MRT – *E*s of the overall dimensions.

	R^2	p	F_{stat}
Height	0.0002315	0.9258	0.008801
Length	0.00334	0.7232	0.1273
Width	0.01836	0.4044	0.7108

linear relationship between the MRT scores and the *E*s of the overall dimensions.

In addition, differences between IVE and nIVE in their effect on the relationship between MRT scores and *E*s of the overall dimensions were investigated. The MRT scores were plotted against the *E*s in each VE. Scatter plots and regression lines are presented in Figure 11. Low R^2 values indicate that MRT scores alone are not sufficient to describe the *E*s for any of the dimensions in any of the VEs.

2) ESTIMATIONS OF THE HORIZONTAL DISTANCE BETWEEN PARTICIPANTS' HEEL AND BACK

Four participants that reviewed the scooter in the IVE overestimated, 15 participants underestimated, while one participant correctly estimated the size of the horizontal distance between participants' heel and back. In the real world, the difference in over- and underestimates was smaller; eight participants overestimated, seven participants underestimated, while five participants correctly estimated the dimension. Acquired results are presented in Table 6. Differences in the *E*s between RW and IVE were not further analyzed employing statistical tests within the presented paper. Investigation of differences in spatial perception between RW and IVE is beyond the focus of the study. Results of this task are analyzed in the next section to investigate their effect on the correctness of affordance judgments in conjunction with a VE.

E. JUDGMENT OF A BODY-SCALED AFFORDANCE (INTRINSIC TASK)

Accuracy of the judgment was analyzed by comparing measured participants' anthropometric measurements (actual external measure) with dimensions of the scooter (actual external measure). In particular, the estimated value of the horizontal distance between participants' heel and back (as

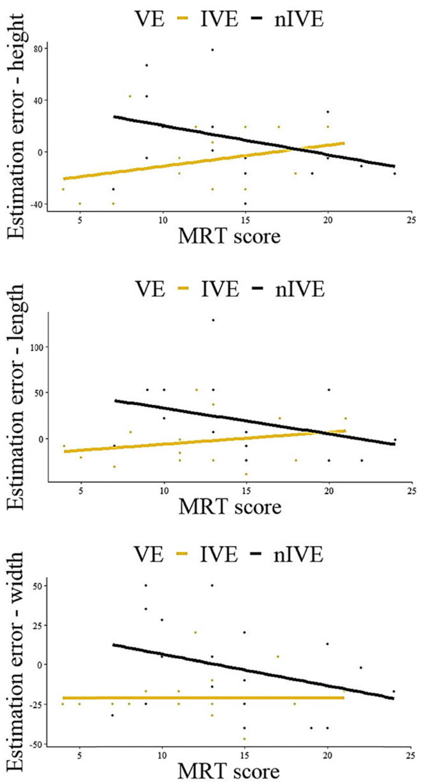

FIGURE 11. Linear regression: *E*(height) – MRT (top), *E*(length) – MRT (middle), *E*(width) – MRT (bottom).

TABLE 6. Estimation errors of the horizontal distance.

		Nº	Horizontal distance
IVE	Total	20	16.1% ± 12.6%
	Overestimated	4	21% ± 10.8%
	Underestimated	15	18.6% ± 13.3%
RW	Total	20	22% ± 23.3%
	Overestimated	8	37.6% ± 28%
	Underestimated	7	15.1% ± 11.2%

Form of the values presented in the table is: Mean value ± Standard deviation.
*p < 0.1; **p < 0.05; ***p < 0.01

explained in section IV-D-2; $D_{\text{H-B}}$) was compared with an actual distance between the seat backrest and the starting edge of the feet holders ($D_{\text{SFH-SB}} = 520$ mm). In addition, a distance from the tip of participants' toes and their back ($D_{\text{T-B}}$) was compared with a distance from the finishing edge of the feet holders and the seat backrest ($D_{\text{FFH-SB}} = 800$ mm). It was considered that the scooter affords the participants driving in the preferable driving position if most of the participant's foot (i.e. more than 50%) could be placed on the feet holders. Hence, the scooter affords the participants driving in the preferable driving position if the distance between the seat backrest and participants' heel $D_{\text{(SB-H)m}}$ is at least ($D_{\text{(SB-H)m}} = 520 - 0.5$ * foot length) mm, while the distance between the seat backrest and the tip of participants' toes $D_{\text{(SB-T)m}}$ is not larger than ($D_{\text{(SB-T)m}} = 800 + 0.5$ * foot length) mm. Whereby, foot length is multiplied by 0.5 because "most of the foot" was defined as at least 50% of the length of the participants' foot.

Table 7 presents the number of participants that (in)correctly judged the driving position affordance and their accompanying confidence in the correctness of their judgment. The number of the participants that were correct and the number of the participants that were incorrect was the same in IVE ($n = 10$), while in nIVE eleven participants were correct and nine participants were incorrect. Thus, a difference between VEs in the number of (in)correct judgments was small.

The following sections present the analysis of differences between VEs in the effect of each independent variable presented in Table 7 (namely, confidence judgment, immersion, MRT score, and E of $D_{\text{H-B}}$) on the affordance judgment. The analysis was conducted in three steps. Firstly, differences between VEs were analyzed regardless of the correctness of the affordance judgment (denoted as "Total" in Table 7). Secondly, differences between VEs were examined considering the correctness of the affordance judgment. More specifically, differences between VEs in the effect of the independent variables on the correctly judged affordances were analyzed separately from these on the incorrectly judged affordances. Finally, differences between VEs in the effect of the independent variables on correct and incorrect judgments within the same VE were investigated. In particular, differences in the effect of the independent variables on the correct and incorrect affordance judgment in the IVE were analyzed separately from these in the nIVE.

1) DIFFERENCES BETWEEN VES IN THE EFFECT OF THE CONFIDENCE JUDGMENT ON THE AFFORDANCE JUDGMENT

The analysis of the participants' judgment of confidence in the correctness of their answers showed that they were more confident in the IVE than in the nIVE, regardless of the correctness of their affordance judgments. *Wilcoxon's rank-sum test* showed statistically significant differences only at the confidence level of 90% ($p = 0.07366$).

The means of the confidence judgments in the correctness of the affordance judgments were higher for the group of the participants that reviewed the scooter in the IVE, as it can be noticed from the boxplots presented in Figure 12. This difference exists for both the group of the participants that correctly and incorrectly judged the affordance. However, *t-test* did not confirm a statistical significance of these differences between IVE and nIVE in confidence judgments of the group that correctly ($p = 0.2202$) nor incorrectly ($p = 0.1197$) judged affordances.

The participants who correctly judged the driving position affordance were slightly less confident in the correctness of their judgment than those who incorrectly judged the affordance in both VEs, as boxplots presented in Figure 12 indicate. *T-test* showed no statistical significance of differences between the groups that correctly and incorrectly judged affordances in the IVE ($p = 0.1419$).

TABLE 7. Affordance judgments clustered by their correctness.

		Nº	Confidence	Immersion	MRT	E of D_{H-B}
IVE	Total	20	76% ± 13.2%*	46% ± 5.8%***	12.7% ± 4.5%	25.7% ± 19%
	Correct judgment	6	71% ± 13%	46.7% ± 3.8%**	13.6% ± 4.1%	28.9% ± 18.5%
	Incorrect judgment	14	80% ± 11.8%	45.2% ± 7.2%**	11.7% ± 4.6%*	22.4% ± 18.6%
nIVE	Total	20	64% ± 22%*	39.1% ± 6.3%***	14.05% ± 7%	38.8% ± 53.1%
	Correct judgment	10	59.1% ± 25.4%	41.6% ± 4.3%**	16.1% ± 5.0%*	34.2% ± 54.5%
	Incorrect judgment	10	70% ± 13.3%	36% ± 7%**	12.4% ± 3.6%*,*	44.4% ± 50.7%

Form of the values presented in the table is: Mean value ± Standard deviation.
*p < 0.1; **p < 0.05; ***p < 0.01

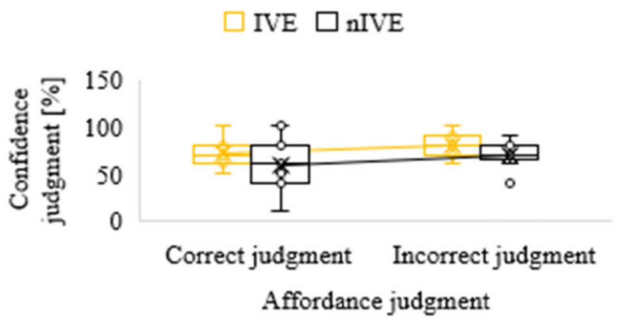

FIGURE 12. **Boxplot: Confidence judgment of the participants that correctly or incorrectly judged the affordance in VEs.**

Similarly, *t-test* did not confirm a statistical significance of differences between the groups that correctly and incorrectly judged affordances in the nIVE ($p = 0.2839$).

2) DIFFERENCES BETWEEN VES IN THE EFFECT OF THE IMMERSION ON THE AFFORDANCE JUDGMENT

Participants' *immersion* was significantly higher in the IVE than in the nIVE ($p = 9.633 \cdot 10^{-5}$), as presented in Table 2.

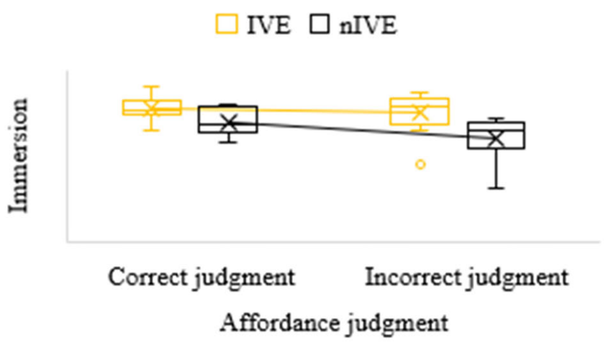

FIGURE 13. **Boxplot: Immersion of the participants that correctly or incorrectly judged the affordance in VEs.**

This aspect is further elaborated considering the correctness of the affordance judgment. Differences between VEs are presented in Figure 13 using the boxplots. The mean value of the participants' *immersion* was higher in the IVE for both the group of the participants that correctly and incorrectly judged the affordance. The results of the *t-test* showed that this difference between IVE and nIVE was statistically significant for the group that correctly judged affordances ($p = 0.01333$). Similarly, *Wilcox rank-sum test* showed that the difference between IVE and nIVE was statistically significant for the group that incorrectly judged affordances ($p = 0.01115$).

Immersion was higher for the participants who correctly judged the driving position affordance than for those who incorrectly judged the affordance in both VEs, as boxplots presented in Figure 13 indicate. Nevertheless, *t-test* did not reveal a statistical significance of differences between the groups that correctly and incorrectly judged affordances in the IVE ($p = 0.7906$). The statistical significance of the differences between the groups that correctly and incorrectly judged affordances in the nIVE was also not revealed by *t-test* ($p = 0.1013$).

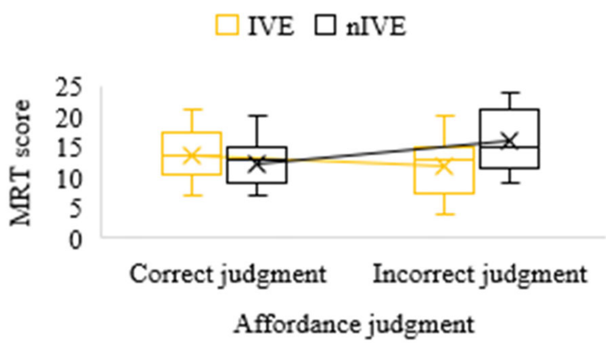

FIGURE 14. **Boxplot: MRT scores of the participants that correctly or incorrectly judged the affordance in VEs.**

3) DIFFERENCES BETWEEN VES IN THE EFFECT OF THE MRT SCORES ON THE AFFORDANCE JUDGMENT

The means of the MRT scores were slightly higher for IVE participants who correctly judged the affordance, as shown in Figure 14. On the contrary, for the group of the participants that incorrectly judged the affordance, the IVE participants had higher means of the MRT scores. The results of the *t-test* showed that this difference between IVE and nIVE was statistically insignificant for the group that correctly judged affordances ($p = 0.4941$). The difference between IVE and nIVE was statistically significant at the level of significance of 0.1 for the group that incorrectly judged affordances ($p = 0.07726$), as results of the *Wilcox rank-sum test* showed.

The participants who correctly judged the driving position affordance in the IVE had higher means of MRT scores than those who incorrectly judged the affordance in the same VE, as indicated by boxplots presented in Figure 14. On the other hand, the participants who incorrectly judged the driving position affordance in the nIVE had higher means of the MRT scores than those who correctly judged the affordance. However, the differences between correctly and incorrectly judged affordances were found to be insignificant in IVE ($p = 0.37001$), as results of *t-test* showed. In nIVE, the differences were confirmed at the 90% level of confidence ($p = 0.08302$).

4) DIFFERENCES BETWEEN VES IN THE EFFECT OF THE E OF $D_{\mathrm{H-B}}$ ON THE AFFORDANCE JUDGMENT

The analysis of the participants' Es of $D_{\mathrm{H-B}}$ showed that the IVE participants had significantly lower errors than those who reviewed the scooter in the nIVE.

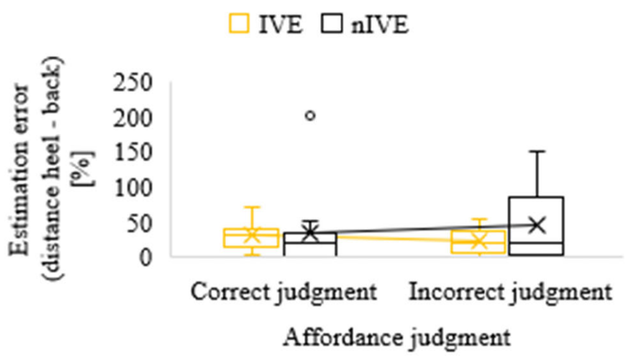

FIGURE 15. Boxplot: *E* made by the participants that correctly or incorrectly judged the affordance in VEs.

The means of the Es were slightly higher for the IVE participants who correctly judged the affordance, as it is shown by boxplots presented in Figure 15. On the contrary, for the group of the participants that incorrectly judged the affordance, those who reviewed the scooter in the nIVE had higher means of the Es. The results of the *Wilcox rank-sum test* showed that these differences between IVE and nIVE were statistically insignificant for both the group that correctly ($p = 0.3058$) and incorrectly ($p = 0.7127$) judged affordances.

The participants who correctly judged the driving position affordance in the IVE had slightly higher means of the Es than those who incorrectly judged the affordance in the same VE. On the other hand, the nIVE participants who incorrectly judged the driving position affordance had higher means of the Es than those who correctly judged the affordance. *T-test* did not confirm a statistical significance of differences between the groups that correctly and incorrectly judged affordances in the IVE ($p = 0.467$). Similarly, the *Wilcoxon rank-sum test* did not confirm a statistical significance of differences between the groups that correctly and incorrectly judged affordances in the nIVE ($p = 0.6459$).

V. DISCUSSION

The conducted study investigated the effect of a visual representation (IVE and nIVE) on the spatial perception of engineering students employing two types of tasks. Namely, extrinsic (perception of spatial properties) and intrinsic (perception of spatial relations; a body-scaled affordance) tasks. The employment of these both types of tasks through the spatial properties and the affordance as measures of spatial perception provides the validation of the findings obtained by each measure and exploration of their relationship. In the extrinsic task, participants estimated the overall dimensions of the folded scooter. In the intrinsic task, participants judged the driving position affordance of the scooter based on the spatial relationship between their body and the 3D CAD model that represented the scooter (their dimensions). For the accomplishment of these tasks, the employment of both intrinsic and extrinsic spatial skills was needed. In particular, an intrinsic-static spatial skill [7] is used to estimate the size of dimensions employing the verbal estimation method (section IV-D-1 and IV-D-2). A judgment of the driving position affordance asks for the usage of the extrinsic-static spatial skill [7]. The intrinsic-dynamic spatial skill was investigated through the MRT [49] (section IV-C). This combination of the employed spatial skills provides an exploration and a discussion of differences in their relationships among IVE and nIVE.

The results of the study help to clarify differences in the effect of IVE and nIVE on the spatial perception of spatial properties (through extrinsic task), affordances (through extrinsic task), and their relationship with accompanying spatial skills. In this way, the study provides findings that are complementary and offer a more inclusive picture of differences in designers' spatial perceptions in VEs. It was assumed that the presented VE mediated by IVR technology is more immersive than one mediated by the conventional 2D user interface. Responses of the participants on the PQ validated this assumption, as it was often a case in related studies (for example, [52]). Following sections discuss the results in more detail.

A. THE ESTIMATIONS OF DIMENSION SIZE (PERCEPTION OF SPATIAL PROPERTIES) IN VEs

In general, it is assumed that IVE improves the understanding of interactions between components of the presented model and its spatial arrangement due to its support of spatial cues [38]. It is also argued that the higher accuracy in estimation of the spatial properties (such as dimensions or distances) of the presented model indicate a better understanding of its spatial arrangement [24]. Analysis of the results of the extrinsic task has shown that Es for the overall dimensions of the folded scooter were smaller in IVE than nIVE. These results answer the first research question and partially confirm the hypothesis from section II that designers' spatial perceptions of 3D CAD model dimensions differ between the IVE and the nIVE.

TABLE 8. Comparison of the *E*s.

	Height	Length	Width
IVE	16.1% ± 12.6%	15.6% ± 13.3%**	18.8% ± 9.4%**
nIVE	22% ± 23.3%	27.0% ± 29.9%**	19.2% ± 15.4%**

Form of the values presented in the table is: Mean value ± Standard deviation.
*p < 0.1; **p < 0.05; ***p < 0.01

The hypothesis is partially confirmed because the analyzed difference of Es in IVE and nIVE was not statistically significant for all the dimensions. As marked in Table 8, a statistical significance of difference was confirmed for the length and the width of the folded scooter, while it was insignificant for the height. Besides, a difference between IVE and nIVE in the Es for the width was statistically significant due to the high difference in the number of over- and underestimations, not in the values of Es. Majority of the participants that reviewed the scooter in the IVE underestimated sizes of all three overall dimensions. This is in line with previous studies of the perception of spatial properties conducted in VEs [24], [34]. The underestimations are often explained with the effect of low fidelity of the visual representation on the perception of spatial information [44].

Considering the differences in Es of the overall dimensions within each VE, it was noticed that the values of Es might depend on the actual size of the assessed dimension. In the nIVE, Es were larger for the larger sizes of dimensions. In the IVE, on the contrary, Es were smaller for the larger sizes of dimensions. Similarly, Gîrbacia *et al.* [34] reported on the accuracy of the estimation of the depth being higher for large values of the depth. Further, the Es between dimensions were statistically significantly different in both VEs. The significance was confirmed between height and width, and length and width in both VEs. It may be that significance of the difference between these dimensions is related to the order in which dimensions were estimated. Yet, these differences in the Es, depending on the place in the order in which dimensions were estimated, were statistically insignificant in both VEs. As a result, it seems that the order of estimations is not directly relevant for the values of Es, based on the available data. Regardless, availability of the larger sample may reveal a significant effect of the order in which dimensions sizes are estimated on the value of the Es.

Results of the regression analysis in the conducted study did not reveal a linear relationship between the measured spatial skill of mental rotation, as an indicator of participants' prior spatial cognition ability, and spatial perception of spatial properties in VEs. The scatter plots and the regression analysis were used to check the linearity between the MRT scores and the Es of the overall dimensions. However, no evident linear relations were found. The general trends displayed in Figure 11 suggest that the spatial skill of mental rotations has different effects on spatial perceptions of spatial properties in IVE and nIVE for all three dimensions, but the absence of well-fitted models prohibits any inferences.

B. THE JUDGMENT OF THE BODY-SCALED AFFORDANCE (PERCEPTION OF SPATIAL RELATIONS) IN VEs

The product should be designed as part of a human and machine system in which the operator, the machine, and the environment in which it operates all function effectively [1]. Since humans vary in size, factors such as height or arms reach need to be considered when designing products. It is usual to design product for an average person, but that approach does not necessarily ensure the fit of the product's UIEs to the users. Brown and Blessing [53] suggest the usage of affordances as a supplementary perspective to functional reasoning in the design process. A product should fit the physical characteristics of a user, but possible actions that can be performed on or with it should also be perceptible with a minimal cognitive effort [4].

In the presented study, human factors in the design of the scooter were assessed through the intrinsic task encompassing judgment of a driving position affordance of the scooter. It was hypothesized that the enhanced spatial perception of the fit of the UIEs as body-scaled affordances differs between the IVE and the nIVE. This was grounded in studies such as [17], [24], [34], [38] reporting on the positive effect of IVE on spatial perception due to properties such as first-person view, eye-height reference, spatial updating, stereopsis, and multimodal interaction. The conventional 2D user interfaces are usually not characterized by such properties. Nevertheless, the results of the study reject this hypothesis and answer the second research question indicating that the likelihood of making the correct judgment of the affordance was similar in the IVE and the nIVE. One possible explanation of such result may be related to the inability of participants to see their body in IVE, which tends to be important when considering body scaling during the judgment [44].

The analysis of the effect of the independent variables on spatial perceptions in VEs aimed to support an understanding of the potential reasons behind the extracted results.

Considering the correctness of participants' answers, results indicate that participants who correctly judged the driving position affordance were as confident in the correctness of their judgment as those who incorrectly judged the affordance in both VEs. Regardless of the actual correctness of their affordance judgment, engineering students were more confident in the accuracy of their judgment in the IVE than in the nIVE. It may be that the higher experienced presence in the IVE (see Table 2) affected their confidence judgments. For example, Spence, Dux and Arnold [54] suggest that higher confidence might be related to the estimation of accumulated sensory information provided by virtual representation as highly reliable. Similarly, Hannah, Joshi and Summers [13] reported on participants' high levels of confidence when reviewing a high level of fidelity representations.

As for the effect of immersion on the affordance judgment in VEs, the statistically significant difference was found between the VEs in the levels of immersion they provide. This difference remains significant while considering the correctness of the affordance judgment. Visual inspection of the lines (see boxplot in Figure 13) and results of inferential tests indicate that the differences are not significant between correct and incorrect affordance judgment within the IVE nor nIVE.

When it comes to the MRT scores, visual inspection of boxplots indicates that their influence on the affordance judgments differs between the VEs. Still, these differences were not statistically significant in all cases. The difference was found between IVE and nIVE in the effect of the MRT scores on the incorrect affordance judgments. Additionally, a difference was significant between correct and incorrect affordance judgments within the nIVE. Higher means of the MRT scores can be noticed among the engineering students that incorrectly judged the affordance in the nIVE, when compared to those who correctly judged it. The trend line is the opposite in the IVE. However, the available data is not sufficient to statistically confirm all differences due to the sample size limitations. As such, they stream a need for a more comprehensive future research of the effect of the spatial skill of mental rotations on the spatial perceptions of body-scaled affordances in VEs.

By their definition, affordances depend on the relationship between the environment and the user (as discussed in section II-C). Nevertheless, there is some ambiguity in the literature on whether affordances are perceived directly or spatial properties (such as dimensions of the environment and the anthropometric measures of the user) have to be firstly perceived in extrinsic units and then compared employing cognitive processes to enable perception of affordances [4], [22]. The conducted experiment does not resolve this ambiguity. Nevertheless, its results allow for an analysis of a difference between the VEs in the effect of engineering students' spatial perceptions of anthropometric measurements of their body on their spatial perceptions of body-scaled affordances. Based on visual inspection of the boxplots presented in Figure 15, the results indicate that the effects of engineering students' spatial perceptions of anthropometric measurements of their body on their spatial perceptions of body-scaled affordances differ in IVE and nIVE. However, this difference was not confirmed with statistical significance.

Considering the perspective of perceiving affordances, it may be that ecological perspective is applicable in the IVE, while model-based perspective in the nIVE. The results might indicate that the participants do not necessarily map estimations of their anthropometric measures to the actual dimension of the scooter to judge the driving position affordance in IVE. It might be that an accurate perception of spatial properties using extrinsic metric is not needed in IVE to judge the affordance, as Fajen and Philips propose [22].

Furthermore, the results of the presented study suggest that participants' intrinsic-static spatial skill is relevant for the body-scaled affordance judgment in nIVE, while in IVE participants were able to correctly judge the body-scaled affordance regardless of their intrinsic-static spatial skills. Other scholars (such as [22], [40], [44], [55]) argue that the availability of eye-height reference mitigates the need to rely on the perception of the spatial properties (such as distances) and make it possible for affordances that depend on dimensions of the body (i.e. body-scaled affordances) to be directly perceived. Since participants were provided with the eye-height reference in IVE, the results of the conducted study can be related to these findings.

C. LIMITATIONS OF THE STUDY AND OUTLINES FOR FURTHER WORK

Some limitations of the presented study should be noted. The first methodological limitation concerns the participants of the study. The experiment was conducted with engineering students so the generalization of the reported results should be made with caution. It is possible that results would be different for experienced engineers. As such, it is advisable to repeat the study with more experienced practitioners. The considered sample of engineering students that participated in the conducted study allowed for the performance of the statistical analysis and achieving some statistical evidence. Regardless, the sample is not sufficient for the generalization of the reported suggestions and performance of the additional tests with two independent variables. Because of that, the number of participants should be larger in future studies to enable more insights into differences in spatial perceptions between IVE and nIVE, and effects of the independent variables on them.

The first hypothesis was only partially confirmed since statistically significant differences between IVE and nIVE were not found for all the three overall dimensions. The study did not provide an explanation of the reasons in the background of such results. However, the results indicate some differences in Es along dimensions and concerning the order of their size estimations that might provide potential answers if they are more thoroughly researched in future studies. Other scholars have reported on similar inconsistencies in the statistical significance of a difference when a task included verbal estimations. It may be that designers are better in estimating sizes of specific dimensions because of the properties of the human vision. For example, Wraga [40] concluded that availability of eye height reference resulted in higher accuracy in the estimations of height, but it did not affect estimations of width since the supplementary size information (eye height) is a more natural metric for an object height than width. It is suggested to improve further research with the inclusion of the additional analysis concerning the orientation of the reviewed model.

IVE and nIVE, as visual representations, rely on spatial information to communicate with users. The effectiveness of the employment of these representations may largely depend on the ability of the users to comprehend this spatial information [14]. In the exploratory purposes and with the aim of proposing the avenues for further work, the study encompassed the first step for identification of differences in the relationship between different spatial skills and spatial perceptions of spatial properties and the affordances as an aspect of a design understanding. Differences between VEs are identified in the effects of an intrinsic-dynamic spatial skill of mental rotation on spatial perceptions of the spatial properties and the body-scaled affordance. Along with that, results indicate a difference between VEs in the effect of an intrinsic-static spatial skill on spatial perceptions of the body-scaled affordance. Due to the limitations related to the sample size, it was not possible to conduct further analysis to investigate differences between the VEs. Nature of the relationship between different static and dynamic spatial skills, as an indication of the prior spatial abilities, and spatial perception of spatial properties in VEs should be more thoroughly investigated in future studies. This might provide insights into the relevance of spatial skills on the performance in VEs. There are two commonly discussed hypotheses about the effect of the IVE (in comparison to the nIVE) on the task performance and learning of users [15]. The ability-as-compensator hypothesis argues that the benefits of the IVE are more noticeable for users with poor spatial skills because the IVE reduces the cognitive loads and support them in constructing mental representations [16]. On the contrary, the hypothesis of ability enhancement argues that the IVE increases the cognitive loads because of the multimodal capabilities and, in this way, reduces task performance and learning gains of the users with poor spatial skills [15]. Hence, further empirical and theoretical elaboration is needed to better characterize the relationship between the spatial skills of designers and aspects of their design understanding, such as the spatial perception of a design solution.

Finally, as previously noted in section V-B, the next methodological limitation is related to the employed technology and the inability of the participants to see their body (self-avatar) in the IVE. It is possible that the lack of direct visual information on participants' anthropometric measurements affected their spatial perceptions of the body-scaled affordances. In the next studies, it is advisable to enable this option.

VI. CONCLUSION

The presented study investigates differences in designers' spatial perceptions of spatial properties and affordances when a design solution is presented by a 3D CAD model in the IVE (mediated using IVR technology) and the nIVE (mediated using the conventional user interface). The experiments, performed with 40 engineering students, incorporated two tasks specific for the activities within a design review. They encompassed an estimation of the size of the overall dimensions of the mobility scooter as the reviewed design solution (extrinsic task) and judgment of a driving position affordance in regard to the design of the seat and feet holders of the scooter (intrinsic task). The goal of the presented study was to contribute to a better understanding of the effect of IVE on the spatial perception of a visual representation of design solutions and its differences when compared to nIVE. Thus, the study helps to clarify aspects of design understanding for which the employment of the IVE might be beneficial in comparison to nIVE. The results suggest that the assessments of the spatial perception of the overall dimensions and the body-scaled affordance, used in the conducted study, provide new findings and insights for the spatial perception of a design solution in VEs. In particular, the findings of the study indicate that engineering students more accurately perceive spatial properties in the IVE than nIVE. On the other hand, it is suggested that the likelihood of making the correct judgment of the affordance is similar in both VEs. Hence, the results of the conducted study indicate that spatial perception as an aspect of a design understanding differs between the egocentric and allocentric visual representations in extrinsic, but not in the intrinsic tasks. Based on the obtained insights, the study outlines several avenues for future work. It is suggested to further investigate the effects of VEs on the level of designers' spatial skills needed for design understanding and relationships among them. To gain a more comprehensive understanding of spatial perceptions in VEs, future studies should include more spatial properties (such as shapes, orientations, or rotations of parts) and affordances (such as grasp-ability of the parts or assembling possibilities) of various design solutions.

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FANIKA LUKAČEVIĆ received the M.Sc. degree in mechanical engineering from the University of Zagreb, Croatia, in 2020. She is currently employed as a Research and Teaching Assistant at the Chair of Design and Product Development, University of Zagreb.

STANKO ŠKEC received the M.Sc. degree in mechanical engineering and the Ph.D. degree from the University of Zagreb, Croatia, in 2010 and 2015, respectively. He was appointed as a Visiting Assistant Professor with the Technical University of Denmark, Kongens Lyngby, from 2018 to 2019. He is currently an Assistant Professor with the Chair of Design and Product Development, University of Zagreb. His research interests include related to the multidisciplinary field of the product design and development, primarily focusing on management and monitoring of development processes and activities, as well as on studies of distributed work and virtual collaboration.

MARIJA MAJDA PERIŠIĆ received the M.Sc. degree in mathematics and the Ph.D. degree in computer science from the University of Zagreb, Croatia, in 2015 and 2020, respectively. Her primary field of research and scientific focus is agent-based simulation of information processing and interactions in teams developing technical systems.

NIKOLA HORVAT received the M.Sc. degree in mechanical engineering from the University of Zagreb, Croatia, in 2017, where he is currently pursuing the Ph.D. degree in mechanical engineering. His primary field of research and scientific focus is analysis and evaluation of teamwork in design.

MARIO ŠTORGA received the M.Sc. degree in mechanical engineering and the Ph.D. degree from the University of Zagreb, Croatia, in 1997 and 2005, respectively. He is currently a Full Professor with the Chair of Design and Product Development, University of Zagreb. He is also appointed as a Visiting Professor with the Luleå University of Technology, Sweden. His research interests include product development methods, engineering design ontology, product lifecycle management, knowledge management, innovation management, information evolution structuring and visualization, complexity management, teamwork modeling and management, systems engineering, and cognitive enterprises and systems thinking.