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Exploring the use of Augmented and Virtual Reality in architectural and urban simulation laboratories: a study of Top 100 universities in QS Ranking

Introduction

Virtual Reality (VR) and Augmented Reality (AR) are increasingly used in various activities and are integrated into education and research in different fields, including Architectural Engineering and Construction (AEC) and urban design (Ummihusna e Zairul 2022; Whyte 2002). Portman et al. (Portman, Natapov, e Fisher-Gewirtzman 2015) presented an overview of the use of VR in architecture, landscape architecture, and environmental planning, highlighting the benefits of supporting design communication, visualization, and evaluation with VR by testing architectural design alternatives. However, as Portman argues, the application of VR in research and education shouldn't be focused on visualization only; moreover, an interdisciplinary approach in the field of urban simulation can be beneficial in education and research, as well as professional practice (Bosselmann 2005).

To outline an updated picture of the use of AR and VR in education and research at universities of architecture, urban design, landscape architecture, and civil engineering, this paper presents the research outcomes of an investigation aiming to review the use of VR and AR in urban simulation laboratories. To do this, the top 100 universities in the "Architecture and Built Environment" of the Quacquarelli Symonds (QS) university ranking system were analyzed to assess the types of technologies, or combinations of technologies, currently applied in courses, research, and collaborative projects. In this framework, our research questions are:

Q1. What is the current state of VR and AR technologies utilization in simulation laboratories at top-ranked universities specializing in architecture, urban design, landscape architecture, and civil engineering?

Q2. What are the geographical distribution and concentration patterns of VR and AR laboratories in the top-ranked universities for "Architecture & Built Environment"?

Literature review

The AR/VR visualization modalities favor the production of easy-to-understand scenarios to support the comprehension of design solutions and their progress from conceptualization to construction, including at a 1:1 scale. Gebczynska-Janowicz (Gebczynska-Janowicz 2020) surveyed architecture school students about their experiences in learning CAD skills and found that just 29% of students learned 3D modeling tools before university courses, and the majority of them (69%) found interest in these modalities thanks to university classes. Similarly, Soliman et al.

(Soliman et al. 2021) highlighted the need for designing effective teaching methods to maximize the potential benefits of VR in project design education; they propose to use a constructivist and variation learning approach, meaning that learners need to construct knowledge toward the exploration of alternatives and the direct experience of the effects of their choices, that is what VR/AR can help to experiment. Dvo et al. (Dvo et al. 2005), when describing the development of their VR center for architecture students, highlighted the potential of VR in improving students' skills in visualizing and solving three-dimensional problems, which is essential in preparing them for professional practice. Additionally, Fonseca et al. (Fonseca et al. 2021) reported that virtual serious games could increase students' motivation and interest in architectural and urban design education. The reviewed literature also indicates that using VR technology in education can improve students' design and problem-solving skills; for instance, Bashabsheh et al. (Bashabsheh, Alzoubi, e Ali 2019) found that VR technology can enhance students' understanding of building construction phases and improve their ability to visualize and communicate design ideas. Their work aims to integrate traditional education methods with VR, bringing a four-dimensional representation (geometry and transformations in time) of reality into a classroom and expanding the opportunities to experiment with the actual application of theoretical lessons.

AR is a valuable modality for ubiquitous learning that can be used for matching information with specific targets in the real world, generating strong associations of ideas (Chu et al. 2019), or engaging students to deepen their knowledge of places and design processes principles (Kerr e Lawson 2020). Different studies have explored the potential of AR for designing and planning on-site (Imottesjo et al. 2020; Search 2016; Thomas et al. 2011), proposing a spatial AR system that supports creating complex environments by allowing users to view virtual models overlaid on the real-world environment in an interactive process. The teaching process can also involve students manipulating 3D architectural elements to foster the connection of the design solution with the real world (Diao e Shih 2019). One advantage of AR is that it can be generally processed directly by mobile devices; at the same time, on the contrary, is that some issues that can affect a fluent experience with this solution are related to the technical capability of the device, e.g. gyroscope and the compatibility of the software of the GPS precision and AR engine with the device operative system.

Despite the potential benefits of VR and AR technology in education, some challenges and limitations should be considered. Difficulties in architectural education, especially in the first years, may lay on the need for a base knowledge in 3D modeling, texturing, and coding that may increase the cognitive load requested to students (Diao e Shih 2019; Sánchez Riera, Redondo, e Fonseca 2015). Davila Delgado et al. (Davila Delgado et al. 2020) highlight that while AR and VR can provide realistic scenarios for acquiring knowledge and skills in architectural and engineering constructions, reducing costs, and improving safety while learning practical procedures, these technologies are not yet extensively diffuse modalities in the AEC industry mainly due to technical issues and low investment in acquiring devices. Anyhow, Milovanovic et al. (Milovanovic et al. 2017) propose the use of these modalities to overcome pedagogical challenges in traditional education to keep continuity in the several representations students produce from 2D to 3D.

By the way, scholars agree that collaborative design approaches can be favored by systems such as Tangible User Interfaces (TUIs), AR, VR, and immersive environments; the advantage of using an immersive environment is integrating the three-dimensional representation with the iterative feedback of face-to-face dialogue (Milovanovic et al. 2017). For instance, integrated systems such as the CORAULIS environment show a mixed SAR system application involving a table-top with augmented plans/mock-ups and an immersive screen where several people can discuss the project alternatives. Tangible User Interfaces (TUI) are human-computer interactive systems able to link physical tokens and digital elements in an interactive way (Shaer 2009). An earlier experiment of augmented projection for architecture was conducted by Raskar, Welch, and Chen (Raskar, Welch, e Wei-Chao Chen 1999), who presented a table-top Augmented Reality system that merged physical models with projected imagery. Dias et al. (Dias et al. 2002) used tangible markers to manipulate basic geometries to develop a conceptual architectural design. Kim and Maher (Kim e Maher 2008) conducted a study on the impact of TUIs on spatial cognition during collaborative design; they found that using TUIs reduced cognitive load in performing spatial tasks, in particular, managing spatial relations, and improved users' ability to explore, manipulate, and communicate spatial concepts. Maquil et al. (Maquil et al. 2018) checked the effects on communication and engagement levels using a Geographic Tangible User Interface involving different types of professionals; the authors evaluated a relevant change in inducing more active participation and generating more discussions with a playful tool that is also usable for laypeople.

Method

The top 100 universities in the QS World University Rankings for "Architecture & Built Environment" in 2022 were analyzed to list research and/or education laboratories of these institutions that are active in the fields of architecture, civil engineering, urban design, urban planning, and mobility simulation. We collected data from institutional websites, social media platforms, and other sources that published information on their activities. We classified each laboratory's expertise with the VR and AR visualizations adopted based on the official laboratory description, declared research, courses, and events presented online. Beyond the declared involvement in research, courses, and other students' activities, we also verified if they conduce collaborative processes with private companies, citizens, and public administrations. All the information collected is recorded in a PostgreSQL database linked to a Django app designed for this research. This app was designed to store and aggregate data and present related statistics as maps and charts. The worldwide geographic distribution of the laboratories and the instances of AR and VR expertise expressed in their websites are calculated using this tool and represented on a Choropleth map. The involvement of laboratories in academic research, courses, and workshops, support for student individual activities and projects, as well as citizen participation processes, are all examined; these activities often overlap, and a Venn diagram of frequencies is calculated to highlight these overlaps. To identify the equipment of the university laboratories, we visited the main website of the laboratory; we also searched for their pages on social networks such as Facebook, LinkedIn, and Instagram; we also searched for other independent websites or blogs presenting their work. All laboratory equipment information has been recorded, including the specific brand and model, when available; if these details were not explicit, we identified the device type from the laboratory's pictures. We recorded whether a device was available or not and assessed the kind of device used in the laboratory. The list of devices and tools was then organized into technical categories and related subcategories.

- *Visualization/Interaction Devices*: Head-Mounted Displays, immersive projected environments, mobile/tablet, holographic display
- *Motion and Sensing Equipment*: motion capture systems, environmental sensors, neuro-physiological sensors
- *Audiovisual production equipment*: 360 cameras, 3D scanners, microphones, projectors, speakers, green screens / room
- *Vehicle / pedestrian simulation equipment:* treadmills, driving simulator cockpits, VR steering
- *Computer clusters/servers*
- *Human-Computer Interaction Equipment*: multi-users touch screens, Tangible User Interfaces, and Haptic Interfaces
- *Unmanned aerial vehicle equipment*: drones

We then calculated the occurrences of tools and devices found for each case; this measure does not consider the number of owned devices but just the presence of a type since it was not possible to verify how many copies of the same device are owned by a laboratory.

Results

We identified 34 laboratories dedicated to urban scenario simulation using VR, AR, and driving simulations from the top 100 universities classified in the QS ranking of the Architectural and Built environment. Most of them are concentrated in Great Britain (20. 6%), followed by the United States of America at 17.6%; Italy at 11.8%; China at 11.8%; Australia at 6.0%; Germany at 6.0%. The remaining percentage is equally distributed among the following countries: Sweden; New Zealand; Norway; Netherlands; Monaco; France; Finland; Spain; Switzerland. The geographic distribution of these laboratories and the percentages by country are represented in Fig. 01. The Ven diagram in Fig. 02 shows that 26.5% are focused on academic research; 17.6% are linked to specific structured courses and are involved in research, too; 14.7% supports individual students' activities besides research projects; 5.9% mix the academic research with support to specific courses or students' individual activities. There are no laboratories devoted to courses or collaborative projects only. 5.9% are involved in academic research and collaborative projects; 8.8% mix academic research with collaborative projects and individual student projects supporting; 2.9% involved in collaborative projects offer support for student activities as well. 8.8% focus on supporting students' activities only. The equipment and the activities described on the laboratories' websites involves both VR and AR visualization modalities (Fig. 03). 46.4% apply the VR modality only, while 46.4% can use both VR and AR; only 7.2% focus on AR only. Looking at the percentage of declared device types by all collected laboratories sample, it results in: 48.1%

visualization/interaction devices; 15.9% motion and sensing equipment; 14.8% audiovisual production equipment; 10.8% transportation/pedestrian simulation equipment; 5.2% computer clusters/servers; 3.2% human-computer interaction equipment; 2.0% unmanned aerial vehicle equipment.

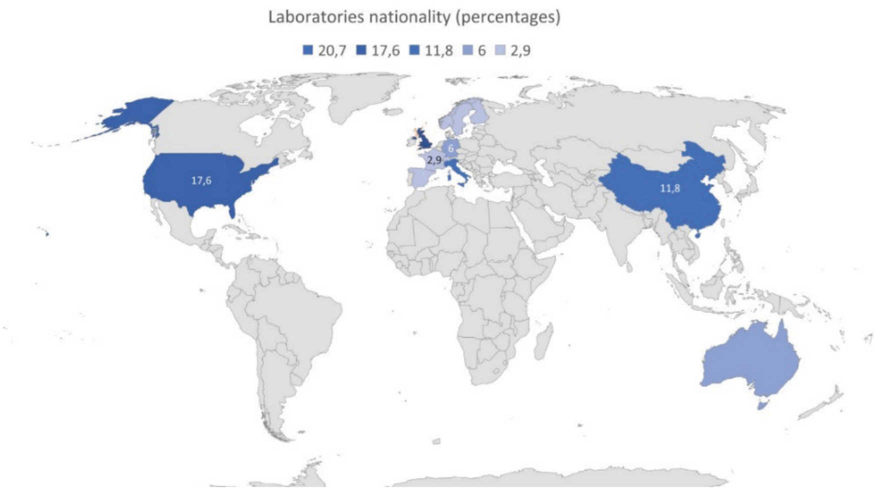

Fig. 01 Geographic distribution of the laboratories applying VR, AR, and driving simulation for urban scenario simulation among the top 100 Architectural and Built environment universities according to the QS ranking.

Source: chart and map drawn by the authors.

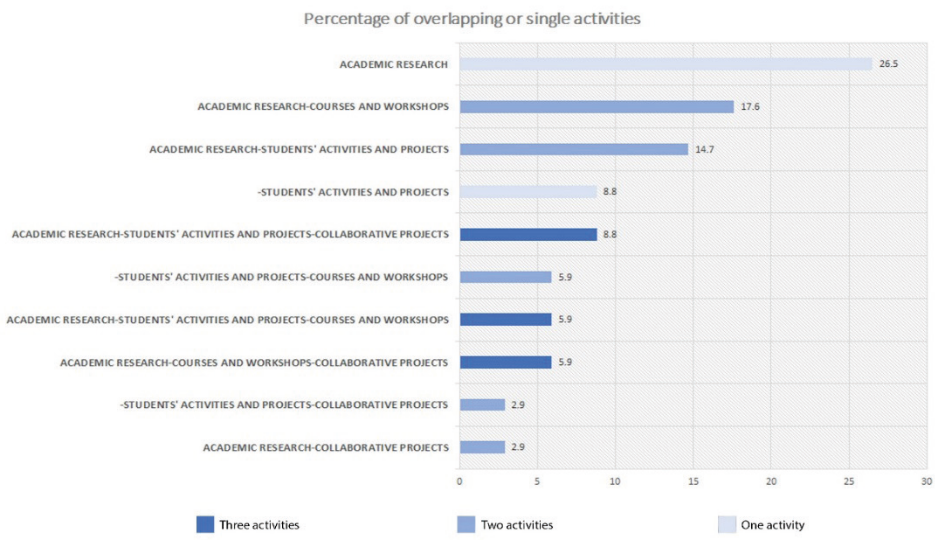

Fig. 02 Venn diagram of laboratories activity types. The diagram shows how many times the activities are declared exclusive or how they are combined.

Source: diagram drawn by the authors.

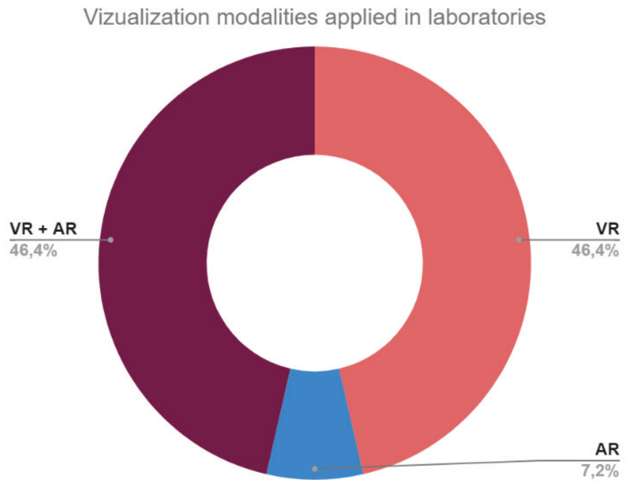

Fig. 03 Visualization modalities applied in laboratories. 46.4% focus on VR only, 46.4% work on both VR and AR; 7.2% are focused on AR only.

Source: chart drawn by the authors.

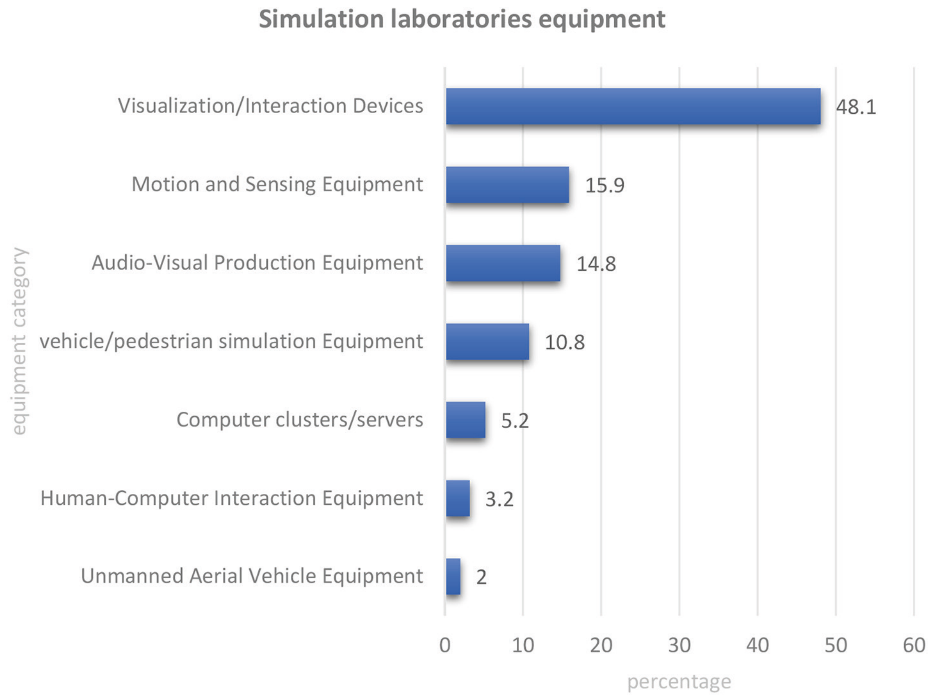

Fig. 04 Percentage of declared equipment (by category) in the laboratories sample.

Source: chart drawn by the authors.

The laboratories further described represent a sample of the aim, equipment, and activities hosted by the universities to develop a seamless process that links research, educational, and planning purposes in urban development.

At the Politecnico di Milano, two laboratories are involved in simulations with different aims: Labora (Fig. 05), provides mainly students with a cylindrical immersive environment and a treadmill to develop projects checking the effects at a real size scale; Labsimurb (Fig. 06) employs AR/VR visualization modalities with mobile/tablet, HMD, a Luminous Planning Table (LPT), environmental sensors, physiological sensors for evaluating the person-environment relationship in terms of well-being and comfort, applying these technologies for multisensory urban design and masterplan, social impact assessment, experiential walks, collaborative processes. At the Eidgenössische Technische Hochschule Zürich (ETH), the Chair of Cognitive Science (COG) (Fig. 07) of provides architecture, urban planning, and engineering students with an interactive environment to learn a human-centered and evidence-based approach to building design. The laboratory hosts a CAVE immersive environment, a driving simulator system, and sensors such as eye-tracking and skin conductance to track the observer experience with the simulation. Architectural students receive education on spatial cognition applied to the built environment and how different layouts affect the observer's reactions.

At MIT, the Media Lab developed in 2013 a Tangible User Interface named CityScope, a Luminous Planning Table for collaborative educational and professional design processes. The platform can track physical tokens placed on the table; the participants can freely reconfigure the token, representing quantities of specific urban functions; a computer program can dynamically calculate the impact of functional block compositions and provide feedback as projections onto the table and charts on a screen. At the University of New South Wales Sidney (UNSW), the City Analytics Lab (CAL) (Fig. 08) is involved in research and teaching for master classes. The CAL laboratory has wide multi-user touch screens, three VR/AR rooms, a Tangible Table sandbox, and an observation room. This facility aims to support and improve city planning and decision-making to develop sustainable and resilient cities.

At the University of California Berkeley, the XR lab is focused on architecture, urban planning, and climate change issues. The methods employed in the laboratory include parametric and generative design and scientific simulations. This laboratory provides didactical support in architectural courses using HMD and mobile applications.

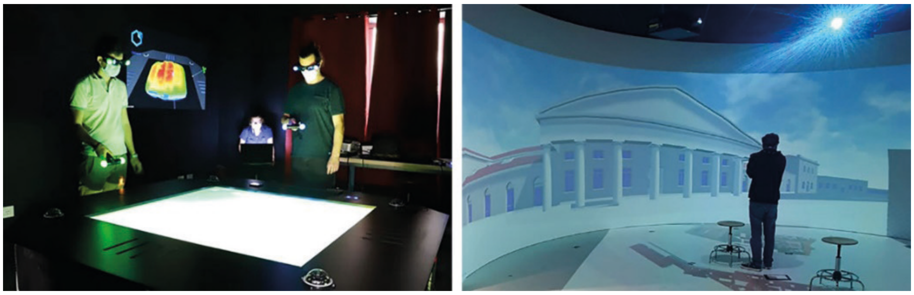

Fig. 05 Labora, Politecnico di Milano. On the left the holographic table, on the right the cylindrical immersive environment.

Source: LABORA. (2023). Retrieved on March 2023, from https://www.polimi.it/ricerca/la-ricerca-al-politecnico/laboratori/grandi-infrastrutture/labora.

Fig. 06 "Laboratorio di Simulazione Urbana Fausto Curti (labsimurb)" at Politecnico di Milano. On the left, Augmented Reality for public participatory processes; on the right, integration of micro-camera and physical model.

Source: LABSIMURB – Laboratorio di Simulazione Urbana Fausto Curti / Dept. of Architecture and Urban Studies – Politecnico di Milano. (2023). Retrieved 20 March 2023, from https://www.labsimurb.polimi.it

Fig. 07 The Chair of Cognitive Science (COG) of the Eidgenössische Technische Hochschule Zürich (ETH).

Source: The Lab. (2023). Retrieved 16 March 2023, from https://cog.ethz.ch/the-lab.html.

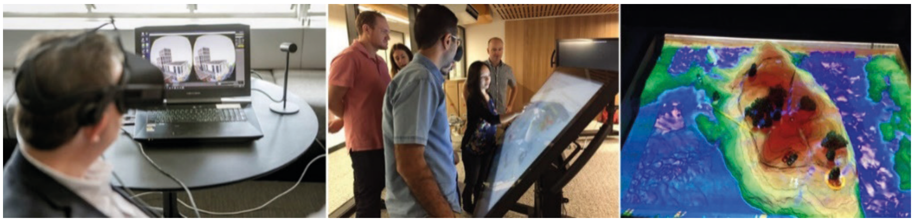

Fig. 08 The City Analytics Lab (CAL) developed by the University of New South Wales Sidney (UNSW).

Source: City Analytics Lab, Retrieved 16 March 2023, from https://www.unsw.edu.au/arts-design-architecture/our-schools/built-environment/our-research/clusters-groups/city-analytics-lab.

Discussion and Conclusions

The analysis of the top 100 universities in the QS World University Rankings for "Architecture & Built Environment" in 2022 revealed 34 laboratories in 28 different institutions dealing with urban scenarios simulation using VR and AR. Some universities host more than one laboratory; less than 30% of the top 100 institutions invested in developing facilities dedicated to VR/AR laboratories for teaching, simulation, and analysis in architecture, urban design, and planning. The geographic distribution of these laboratories showed that most are concentrated in Great Britain and the United States, followed by China, Italy, Australia, and Germany. A significant percentage of these laboratories (26.5%) are focused on research only; however, most laboratories also support individual students' activities and design courses. Regarding the visualization modalities applied by the laboratories, nearly half of them (46.4%) use VR modality only, and an equivalent percentage use VR and AR, while AR represents a residual portion (7.2%). This indicates that the usage of VR is almost double compared to AR solutions.

Regarding the specific devices and tools used by the laboratories, it emerged from the study that visualization/interaction devices were the most commonly used, followed by motion and sensing equipment, for simulation responsiveness or as a tool for analyzing users' reactions to the virtual environment, and audiovisual production equipment. The presence of transportation/pedestrian simulation equipment aims at integrating transportation elements in their simulations for urban planning and design. Even if visualization/interaction is more diffused, laboratories are not merely focused on this aspect, as the presence of other devices demonstrates a variety of activities that use immersive simulations in academic research, courses, students' projects, and collaborative processes. Integrating VR/AR technologies in architecture, urban design, and urban planning education enables a deeper understanding of the complexity involved in real-world project workflows.

By fostering complex spatial thinking and promoting a relational understanding of the city and building layouts, these technologies enhance students' comprehension and subjective experience in their learning process. The potential of these technologies in architecture, urban design, and urban planning is broad at various levels, and, particularly in education, they can foster complex spatial thinking by students by favoring a relational understanding of the city and the layout of buildings and the related subjective experience. Furthermore, employing different tools and devices that support simulations at different scales and involving dynamic feedback can promote a shared vision in design processes and improve problem-solving skills in planning, thus contributing to more effective and innovative design and planning outcomes. These implications of employing such tools make their application in pedagogical processes relevant. Future research on this topic would benefit from a deeper understanding of the actual condition and its evolutionary trend. It would be valuable to explore whether other institutions outside the top 100 invest in developing facilities focused on these modalities employing different assets. At the same time, more detailed insight into the specific activities of each laboratory would be beneficial, mainly if conducted using a collaborative logic of sharing within the laboratory network.

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Authors contribution

The authors' contribution, according to CRediT (Contributor Roles Taxonomy), is described as follows. Conceptualization, B. Piga, L.Pogliani; methodology, G. Stancato, B. Piga; formal analysis, G. Stancato; investigation, G. Stancato; data curation, G. Stancato; writing—original draft preparation, G. Stancato; writing—review and editing, B. Piga, L.Pogliani; visualization, G. Stancato; supervision, B. Piga, L.Pogliani. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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