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Augmented Reality in the Unbounded Research Science Laboratories: Improving College Students' Science Competencies

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ABSTRACT: This research aims to investigate the effectiveness of integrating augmented reality (AR) into science laboratory activities in improving prospective teachers' (PTs) science competencies. This experimental research involved 54 PTs who enrolled in laboratory activities for the Basic Physics Experiment I course, focusing on the topic of heat and temperature, at a University in Ternate city, Indonesia. There are three PTs groups participating in laboratory activities with different strategies: the framework of unbonded research science laboratory activities complemented with AR (URSLA-AR), the same framework without AR (URSLA), and cookbook laboratory activities (CLA). The results showed that the increase in PTs' science competencies was significantly greater in the URSLA-AR group compared to the URSLA and CLA groups. AR technology has been designed into a mobile application package that complements the science laboratory activity module. The findings of the research suggest that educators play a crucial role in developing laboratory activities and selecting those that have the potential for AR technology integration.

Keywords: augmented reality, research skill development, URSLA-AR, URSLA, CLA.

I. INTRODUCTION

The PISA results in 2022 and previous years indicate that Indonesian students' science literacy still needs improvement [1-3]. This suggests that efforts to improve science learning quality need to be continued, particularly through aligning technology use in learning to fulfill equity in science education [4]. The use of technology in learning is essential from early childhood education to higher education. Teachers should carefully select the type of technology integrated into learning to ensure it aligns with students' social and cultural experiences [5]. The appropriate use of technology allows teachers to facilitate students in utilizing it in the most beneficial ways for their learning and development [6]. Science learning should not only be oriented toward concept mastery [7-8] but should also equip students with science competencies that are not only useful for science learning but also serve as a basic foundation for successfully solving life problems in society [9-13]. The quality of science learning is certainly influenced by teacher competencies [14-16]. Science teachers are the main agents in developing students' science competencies [17]. Therefore, efforts to improve the competencies of both in-service teachers and prospective teachers (PTs) need to be carried out continuously. Preliminary research results show that PTs' science competencies are still low [18]. This is supported by findings from competency evaluation results of PTs in Indonesia that still need significant improvement [19-21].

Improving science competencies through innovation in science laboratory activities is one alternative solution that can be implemented [9, 22-23]. Two common methods of science laboratory activities are real and virtual laboratory activities [24]. The laboratory activities conducted using physical equipment is called a real laboratory activity. In contrast to virtual laboratories, all manipulation and visualization of concepts and natural phenomena are carried out through platforms generated and simulated by computers [24-25]. Augmented reality (AR) technology has the potential to integrate both types of laboratory activities [26-27].

The use of AR technology in science laboratory activities can facilitate students to conduct real laboratory activities complemented with digital content availability, particularly for observing microscopic scientific phenomena or presenting abstract scientific concepts [28-29]. Previous research findings indicate that the use of AR in science laboratory activities can improve students' laboratory skills and attitudes toward science laboratories [30], reduce students' cognitive load [31], and increase student motivation to engage in science laboratory activities [32]. Additionally, students who conducted laboratory activities equipped with AR were more motivated and showed improved performance compared to students using traditional experimental materials [33].

AR technology has been proven to be successfully integrated into science laboratory activities. On the other hand, AR cannot serve as an independent learning environment but will be more effective as a complement to the laboratory environment [34]. Science laboratory activities where AR has been successfully integrated include inquiry-based science laboratory [35] and problem-solving laboratory [36-37]. However, previous research focused on students participating in science laboratory activities at elementary or secondary schools. This implies that the design of laboratory activities may not necessarily be suitable when implemented in science laboratory activities at the university level.

This research aims to investigate the effectiveness of integrating augmented reality (AR) into science laboratory activities in improving prospective teachers' (PTs) science competencies. Studies related to this are still rarely found in previous research, and this constitutes the novelty of this research. AR technology, research skill development framework particularly in the scope of unbounded research will be integrated into a mobile application that can facilitate PTs in conducting science laboratory activities.

II. LITERATURE REVIEW

Laboratory activities are an integral part that plays an important role in science learning [38-40]. Laboratory activities are planned learning experiences that allow students to interact with learning materials through observation of phenomena [38]. Through laboratory activities, students can be trained in both hands-on and mind-on skills [41]. However, the lack of facilities and infrastructure often becomes the main obstacle in implementing science laboratory activities [42].

Laboratory activities consist of two types, namely real laboratory and virtual laboratory. Real laboratory facilitates students to make direct observations of real objects, observe interactions between objects in the universe, use the experimental KITs, or use sensors [43-46]. In recent developments, robotic technology has been utilized both in learning activities and in science laboratories [47-50]. Meanwhile, a virtual laboratory facilitates students to make observations through the modeling of real laboratory components in the form of computer simulations built with certain mathematical models to represent experiments in real conditions [25, 51-52]. The presence of AR technology offers a new approach where students can conduct real laboratory activities supported by digital content to visualize abstract concepts [29].

AR can be used as a support for science laboratory activities [34]. AR can combine 2D/3D virtual objects into a real environment and project them in real-time [53-55]. The use of AR can help educators teach abstract concepts, visualizing objects that are too large or too small, too dangerous to observe, too expensive to implement, and can complement real objects [56-57]. AR as a complement to science laboratory activities [34], its use can give students opportunities to interact spontaneously with observed objects [34], can involve students actively in constructing knowledge [59], so that students can explain microscopic phenomena scientifically and connect them with macroscopic phenomena [28].

The PISA 2025 science framework provides an overview of three science competencies and a subset of three environmental science competencies [60]. It also describes the three types of knowledge (content, procedural, and epistemic), the three main contexts (personal, local/national, and global), and the aspects of science identity (valuing scientific perspectives and approaches to inquiry, affective elements of scientific identity, and environmental awareness, concern, and agency). The three science competencies according to the PISA 2025 framework include: 1) explain phenomena scientifically, 2) construct and evaluate designs for scientific enquiry and interpret scientific data and evidence critically, and 3) research, evaluate, and use scientific information for decision-making and action [60].

III. MATERIAL AND METHOD

This experimental research was conducted in the Basic Physics Experiment I course on the topic of heat and temperature to compare the achievement of PTs' science competencies in laboratory activities using various strategies and to evaluate the effectiveness of AR integration in science laboratory activities [61]. The selected laboratory activity focuses on the topic of heat and temperature with the following objectives: a) investigating the effect of heat on a substance's temperature, b) examining the relationship between an object's mass and the amount of heat absorbed or released, and c) formulating mathematical equations to determine the heat required or released by a substance.

1. PARTICIPANTS

A total of 54 PTs participated in this research and were divided into three groups: the experimental group (18 PTs; M = 4, F = 14), control group A (18 PTs; M = 2, F = 16), and control group B (18 PTs; M = 3, F = 15). The PTs are from the physics education and biology education study programs at a University in Ternate, Indonesia. All three groups were taught by the same instructor to eliminate the potential influence of instructor differences on the experimental results. PTs in the experimental group conducted laboratory activities on the topic of heat and temperature, designed based on the Research Skill Development (RSD) framework with six facets of research and five levels of student autonomy, especially the scope of unbounded research [62-63]. These activities were referred to as the unbounded research science laboratory activities with AR assisted (URSLA-AR). PTs in control group A carried out laboratory activities with URSLA activities without AR assistance (URSLA). PTs in control group B conducted laboratory activities using a cookbook laboratory activity (CLA). In these activities, detailed procedures were provided in the laboratory activity module. PTs followed the given instructions precisely to validate the concepts they had previously learned. Table 1 presents the research design used in this research.

Table 1. Experimental design.

Group	Pretest (dependent variable)	Treatment	Posttest (dependent variable)
Experiment	O_1	URSLA-AR	O_2
Control A	O_3	URSLA	O_4
Control B	O_5	CLA	O_6

2. PROCEDURE

The laboratory activities on the topic of heat and temperature were conducted over two weeks, divided into three sessions. In the pre-lab session, PTs completed a pretest to assess their science competencies, including: a) explain phenomena scientifically (EPS), b) construct and evaluate designs for scientific enquiry, and interpret scientific data and evidence critically (CEI), and c) research, evaluate, and use scientific information for decision making and action (REU). After the pretest, PTs in the experimental group conducted laboratory activities based on URSLA-AR. Meanwhile, PTs in control group A followed laboratory activities based on URSLA, whereas PTs in control group B performed laboratory activities based on CLA. Once the laboratory activities were completed, all PTs took a post-test.

3. DATA GATHERING AND DATA ANALYSIS TECHNIQUE

PTs' science competencies data was collected using a test instrument designed in the form of multiple-choice questions, complex multiple-choice questions, and essays, totaling 18 questions. Table 2 shows the science competencies for each ability indicator measured in this research [60]. Before the instrument is used, validation is conducted to ensure its suitability for this research. Data on the improvement of PTs' science competencies were analyzed by determining scores from normalized gain [64].

$$<g> = \frac{\%<S_f> - \%<S_i>}{100 - \%<S_i>} \quad (1)$$

where S_f is the average score of post-tests, and S_i is the average score of pre-tests. Interpretation of $<g>$ score is categorized as high if $<g> \geq 0.70$, medium if $0.70 > <g> \geq 0.30$, and low if $<g> < 0.30$. Further data processing, analysis was carried out using inferential statistical tests with the help of SPPS.

Table 2. Science competencies.

Science competencies	Ability aspect
EPS.	Recall and apply appropriate scientific knowledge (A1). Use different forms of representations and translate between these forms (A2). Make and justify appropriate scientific predictions and solutions (A3). Identify, construct, and evaluate models (A4). Recognize and develop explanatory hypotheses of phenomena in the material world (A5). Explain the potential implications of scientific knowledge for society (A6).
CEI.	Identify the question in a given scientific study (B1). Propose an appropriate experimental design (B2). Evaluate whether an experimental design is best suited to answer the question (B3). Interpret data presented in different representations, draw appropriate conclusions from data and evaluate their relative merits (B41: Interpret, B42: draw appropriate conclusions).
REU.	Search, evaluate, and communicate the relative merits of different sources of information (scientific, social, economic, and ethical) that may have significance or merit in arriving at decisions on science-related issues, and whether they support an argument or a solution (C11: Search, C12: Evaluate, C13: Communicate). Distinguish among claims based on strong scientific evidence, expert vs. non-expert, and opinion, and provide reasons for the distinction (C2). Construct an argument to support an appropriate scientific conclusion from a set of data (C3). Critique standard flaws in science-related arguments e.g., poor assumptions, cause vs. correlation, faulty explanations, generalizations from limited data (C4). Justify decisions using scientific arguments, either individual or communal, that contribute to solving contemporary issues or sustainable development (C5).

IV. RESULTS AND DISCUSSION

1. THE URSLA-AR FRAMEWORK

Table 3 presents laboratory activities based on the URSLA-AR framework, which have been validated using the content validity index (CVI). The URSLA-AR framework consists of three sessions: a) a pre-lab session conducted at home outside of lecture hours, b) a laboratory activity session conducted in the laboratory during lecture hours, and c) a post-laboratory session conducted at home outside of lecture hours. The instrument used to validate the URSLA-AR framework was an expert validation sheet, developed using CVI method. This method was chosen for its ease of calculation and ability to provide detailed information [37, 65-66].

Table 3. Laboratory activities based on the URSLA-AR framework.

Session	Facet of RSD	Laboratory activities that have been developed
Pre-Lab.	Embark & Clarify.	• Observing relevant scientific phenomena (**AR**-assisted). • Identifying the important information related to scientific phenomena. • Asking questions. • Searching information from various reference sources. • Answering conceptual questions. • Formulate the objectives of laboratory activities.
Lab Activity.	Find & generate.	• Studying real-world problem context. • Formulating problems. • Determining tools and materials. • Developing work procedures.
	Evaluate & reflect.	• Testing the equipment function. • Collecting data (**AR**-assisted). • Reflecting.
	Organise & manage.	• Representing experimental data.
	Analyse & Synthesise.	• Analyzing data. • Inferring.
Post-Lab.	Communicate and apply.	• Making laboratory activity reports. • Communicating the results of laboratory activities. • Applying concepts in the context of technological applications in society (AR-assisted).

2. THE RESULTS OF EXPERT VALIDATION AND PORTABILITY TESTING

Laboratory activities developed based on the URSLA-AR framework have been integrated into the laboratory activity module. Table 4 shows that the URSLA-AR module has been deemed highly feasible for use in Basic Physics Experiment I course, as evaluated by experts in scientific content, media, language, and pedagogy. This laboratory activity module is equipped with a mobile apps to support the AR. In this research, the AR application serves as a complementary tool to the laboratory activity module. AR application was developed and designed using Unity 3D software, Vuforia AR, blender 3D for modeling, and Visual Studio for designing mobile apps coding.

Table 4. Validation results of the URSLA-AR module.

Validation expert	Assessment aspect	Percentage (%)	Average (%)
Content expert.	Material description suitability.	85	85
	Material accuracy.	88	
	Material sophistication.	87	
	Presentation technique.	83	
	Presentation support.	84	
Media expert.	Usability.	88	85
	Information quality.	85	
	Service interaction quality.	83	
Language expert.	Language use accuracy.	85	84
	Communicativeness.	84	
	Suitability with student development.	84	

Pedagogical expert.	Learning material presentation strategy.	87	86
	Suitability of laboratory activity for each facet of RSD.	85	

Table 5 presents the results of the portability test for the installability aspect, showing that the AR application, which complements of the URSLA-AR module, can be installed, run, and uninstalled on various android mobile devices, ranging from version 9 to version 14. Figure 1 illustrates the interface of the AR application used as a complement to the URSLA-AR module. AR Visualization of particle motion in cold water (Fig. 1a), particle motion in hot water (Fig. 1b), particle movement during the water heating process (Fig. 1c), heat transfer process in an air fryer (Fig. 1d) and deep fryer (Fig. 1e), all of which are accessed with the help of mobile devices and markers.

Table 5. Results of the portability test.

Mobile device	Android types	Instal	Uninstall
Realme C1 (RMX1811)	9	√	√
Samsung galaxy A7	10	√	√
Samsung galaxy A10s	10	√	√
Redmi note 9 (RJ01DXM)	11	√	√
OPPO A92	11	√	√
Samsung A15	12	√	√
Vivo Y21	12	√	√
Xiaomi redmi note 13 pro plus	13	√	√
Realme note 50	13	√	√
OPPO A18	14	√	√
Samsung Galaxy A04e	14	√	√

(a) (b) (c) (d) (e)

FIGURE 1. AR media display, the visualization of; (a) particle motion in cold water, (b) particle motion in hot water, (c) particle movement during the water heating process, (d) heat transfer process in an air fryer, (e) heat transfer process in a deep fryer.

3. IMPROVING PTS' SCIENCE COMPETENCIES

Table 6 presents the results of parametric statistical tests and effect size values which show that in general the improvement in PTs' science competencies in the URSLA-AR group significantly increased compared to the URSLA group and the CLA group. On the other hand, PTs in the URSLA group significantly increased compared to the CLA group. This shows that the development of science laboratory activities can improve PTs' science competencies. This improvement can be further improved if the developed laboratory activities are equipped with AR technology. The improvement in PTs' science competencies in the URSLA-AR and URSLA groups can be categorized as medium, while in the CLA group it is categorized as low.

Figure 2 illustrates that there has been an increase in each ability of EPS competency in the three groups. The increase in the URSLA-AR group was greater than that of the URSLA and CLA groups. In the three groups, the highest increase occurred in the A1 ability aspect, while the lowest increase was in the A5 ability aspect. In the URSLA-AR group, the increase in the A5 ability aspect was categorized as medium, while the increase in other ability aspects was categorized as high. Only the increase in the A1 ability aspect was categorized as high in the URSLA group. In the CLA group, only the increase in the A5 ability aspect was categorized as low, while the others were categorized as medium.

Table 6. Statistical analysis result of PTs' science competencies.

Description		Group		
		URSLA-AR	URSLA	CLA
Average $\langle g \rangle$		0.609	0.478	0.287
Standard deviation		0.154	0.180	0.071
One-Sample Kolmogorov-Smirnov test (*Sig.*)		0.868	0.885	0.060
Test of homogeneity of variances (*Sig.*)			0.005	
One-Way ANOVA (*Sig.*)			0.000	
Post-Hoc test (*Sig.*)	• Exp. – Control A		0.029	
(Tamhane's T_2)	• Exp. – Control B		0.000	
	• Control B – Control A		0.001	
	• Exp. – Control A		0.782	
Effect size (*d*)	• Exp. – Control B		2.685	
	• Control A – Control B		1.395	

In EPS competency, the impact of using AR technology on improving PTs' EPS competency is very clear. The presence of AR media can help to contextualize real problems through the visualization of scientific phenomena presented [67] so that it can make it easier for PTs to remember and apply appropriate scientific knowledge to explain and predict these phenomena. The existence of microscopic visualizations such as visualizations of particle motion in liquids at cold, warm, and hot temperatures can facilitate PTs to construct their knowledge and be able to provide a correct understanding of science concepts [28] so that PTs can use various forms of representation and translate them. The use of AR media in laboratory activities has given PTs the opportunity to interact spontaneously with the objects observed [68] so that PTs can identify, construct, and evaluate models. In addition, in the context of applying science concepts to society, AR is able to visualize microscopic phenomena of heat transfer flow by convection in modern technological equipment such as deep fryer and air fryer equipment.

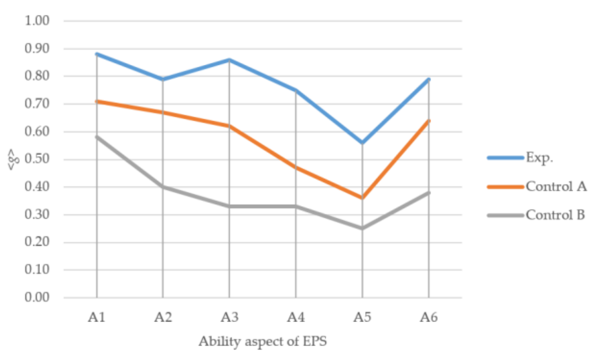

FIGURE 2. The comparison of achievement of ability aspects of EPS competency.

Figure 3 illustrates that in each ability of the CEI competency, PTs in the URSLA-AR group experienced a greater increase than the other groups, except for the B3 ability aspect where the ARSLA group was greater than the ARSLA-AR. In the three groups, the greatest increase was in the B1 ability aspect, while the lowest increase was in the B3 ability aspect. In the B3 ability aspect, the increase in the URSLA group was greater than the URSLA-AR group. However, the differences in these ability aspects were not significantly different. In the URSLA-AR group, only the increase in the B1 ability aspect was categorized as high, while the increase in other ability aspects was categorized as medium. In the URSLA group, the increase in all ability aspects was categorized as medium. In the CLA group, the increase in the B1 ability aspect was categorized as medium, while the others were categorized as low.

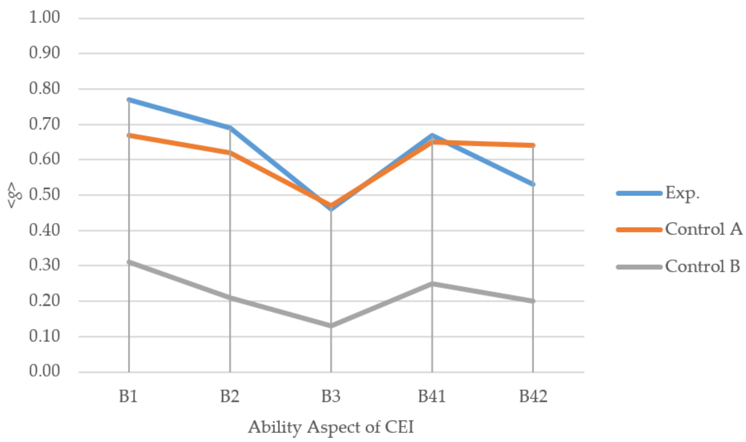

FIGURE 3. The comparison of achievement of ability aspects of CEI competency.

Figure 4 shows that in all groups there has been an increase in each ability of PTs' science competencies. The increase in the ability aspects C11, C12, C13, C2 and C3 in the URSLA-AR group was greater than the other groups. The increase in the ability aspects C4 and C5 for the URSLA group was greater than the URSLA-AR and CLA groups. However, the difference in this increase was not significantly different. In the URSLA-AR group, only the increase in the ability aspects C2 and C3 could be categorized as high, while the other ability aspects were categorized as medium. In the URSLA group, the increase in all ability aspects was categorized as medium. In the CLA group, the increase in all ability aspects was categorized as low.

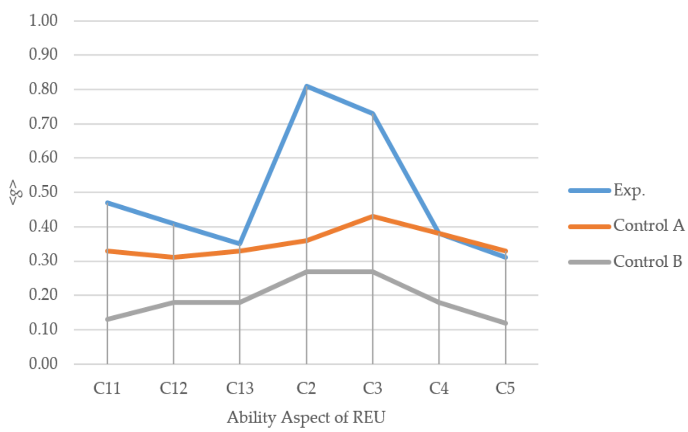

FIGURE 4. The comparison of achievement of ability aspects of REU competency

Integrating AR in science laboratory activities can address the limitations of real laboratory, especially in observing microscopic scientific phenomena [56-57]. AR technology can facilitate PTs to make observations related to the movement of water molecules during the heating process, where this phenomenon is difficult to observe directly by the naked eye. Moreover, AR provides opportunities for PTs to interact virtually with the phenomenon of water molecule movement during the heating process through the manipulation of physical quantities related to this process [58]. Such learning experiences provide opportunities for PTs to build science concepts with more scientific evidence-based arguments [34, 68], thus helping PTs to develop molecular-level explanations of macroscopic phenomena [28].

The support of digital content presented by AR can provide visualization of interesting physical phenomena for PTs to observe, making them more motivated to engage in laboratory activities [29, 32, 58, 69]. Additionally, the visualization of abstract and microscopic concepts can make it easier for them to understand concepts and support the improvement of PTs' performance [33]. The AR technology developed in this research is packaged into a mobile application that can complement laboratory activity modules for heat and temperature topics. Thus, PTs gain more learning experiences through both real laboratory activities and virtual activities [34, 70].

The results showed that developing science laboratory activities significantly improved the PTs' science competencies compared to traditional cookbook laboratory activities. This improvement became even more significant when AR was integrated into the laboratory activities. Therefore, AR technology can serve as an effective alternative learning strategy in science education. Moreover, these findings highlight the crucial role of educators in designing and developing laboratory activities that support effective AR integration. The successful implementation of AR in this study demonstrates its great potential for application in various other laboratory courses, such as chemistry and biology labs. With AR applications packaged into mobile platforms and successfully complementing laboratory activity modules, this study serves as an inspiration for teacher education institutions to develop similar applications for a broader range of experiments. The ease of use of AR applications can encourage PTs to adopt them [71]. Additionally, culturally relevant AR applications or adaptive learning features can significantly enhance their relevance (5). However, a key challenge remains: implementing AR-based science laboratory activities requires PTs to use mobile devices, necessitating supportive policies regarding mobile device usage in educational settings.

V. CONCLUSION

The integration of AR in science laboratory activities for PTs has been successfully implemented by referring to the research skill development framework, particularly the scope of unbounded research (URSLA framework). In its implementation, PTs that conduct laboratory activities based on the URSLA framework significantly increase their science competencies compared to those following a cookbook laboratory activity (CLA). This improvement became even more significant when AR was integrated into the URSLA laboratory activities (URSLA-AR). The results of this research have implications that AR will be more effective when its use is made as a complement in science laboratory activities. The efforts to improve PTs' science competencies present a challenge for educators in developing science laboratory activities, as well as analyzing and determining which activities can effectively incorporate AR technology. Furthermore, the findings of this study highlight the need for policies in educational institutions regarding the use of mobile devices in science laboratory activities.

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Author Contributions

All authors contributed equally to this paper. All authors have read and agreed to the published version of the manuscript. All authors confirm that their authorship complies with commonly acknowledged international criteria (every author had made a significant contribution to the development of the concept, conducting the research and preparing the article, read and approved the final version before publication)

Conflicts of Interest

The The authors declare no conflicts of interest

Data Availability Statement

Data are available from the authors upon request.

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