How Augmented Reality (AR) Can Help and Hinder Collaborative Learning: A Study of AR in Electromagnetism Education

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Abstract—Learning physics is often difficult for students because concepts such as electricity, magnetism and sound, cannot be seen with the naked eye. Emerging technologies such as Augmented Reality (AR) can transform education by making challenging concepts visible and accessible to novices. We present a Hololens-based augmented reality system where collaborators learn about the invisible electromagnetism phenomena involved in audio speakers, and we measure the benefits of AR technology through quantitative and qualitative methods. Specifically, we measure learning (knowledge gains and transfer) and collaborative knowledge exchange behaviors. Our results indicate that, while AR generally provides a novelty effect, specific educational AR visualizations can be both beneficial and detrimental to learning – they helped students to learn spatial content and structural relationships, but hindered their understanding of kinesthetic content. Furthermore, AR facilitated learning in collaborations by providing representational common ground, which improved communication and peer teaching. We discuss these effects, as well as identify factors that have positive impact (e.g., co-located representations, easier access to resources, better grounding) or negative impact (e.g., tunnel vision, overlooking kinesthetic feedback) on student collaborative learning with augmented reality applications.

Index Terms—Augmented reality, collaboration, education, makerspaces

1 Introduction

As augmented reality (AR) is becoming affordable and popular, its increased adoption is generating a growing interest for educational use in formal and informal environments. In the formal space, teachers are increasingly using technology-enhanced hands-on learning activities to foster deep conceptual understanding of STEM concepts, such as interactive simulations or activities involving real-world data. In the informal space, we are currently witnessing the birth of the "maker" cultural movement where everyday people collaboratively tinker with physical and digital materials, to explore, modify or create physical artifacts. In such environments, people engage in self-driven inquiry-based learning, and are indirectly exposed to a variety of STEM concepts. We believe that the maker movement has reached a level of maturity where physical-digital interactions can create spaces for new kinds of learning. In particular, augmented reality has the potential to transform science education by making challenging concepts visible during collaborative learning.

Collaborative learning with augmented reality is a complex process that is not well understood in existing literature, which typically study educational AR impacts on individual learners. As educational AR applications become popular, it is necessary to understand what positive and negative effects are generated by AR experiences, and how AR design features interact with collaborative learning processes. This is especially important with the increased focus on knowledge representation and model use in the next generation science standards (NGSS) [1]. This change represents a larger educational shift that is likely to affect not just pre-colege learners, but also undergraduate students in STEM disciplines. Without this understanding it is unlikely that AR will be used to its full potential and its adoption may suffer due to unmet expectations. While prior research has explored the benefits of delivering educational content through augmented reality in comparison to traditional media such as printed materials, videos, or PC-based simulations, it remains unclear which specific learning processes are influenced by the AR content, and which design features of the AR experience are contributing to collaborative learning [2], [3], [4], [5], [6]. We expand the field of educational augmented reality, through the current study in which we evaluate pairs of learners interacting with an AR electromagnetism application and measure the effectiveness of AR to impact collaboration and learning processes. Beyond measuring beneficial and detrimental effects on learning and collaboration, we also analyze how design features of the application contribute to the observed positive and negative effects of AR.

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Manuscript received 8 July 2021; revised 1 Apr. 2022; accepted 6 Apr. 2022. Date of publication 2 May 2022; date of current version 31 July 2023.
This work was supported by the National Science Foundation under Grant 1748093.
This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Committee on the Use of Human Subjects (CUHS) at Harvard University.
(Corresponding author: Iulian Radu.)
Recommended for acceptance by E. D. Ragan.
Digital Object Identifier no. 10.1109/TVCG.2022.3169980

We focus on a collaborative activity that explores concepts in electromagnetism, and critically investigate the benefits and drawbacks of augmented reality for inquiry-based collaborative learning. Electromagnetism is a topic that is often encountered in both maker spaces and traditional physics classrooms, and is one of the most difficult domains to master for students of all ages [7], [8], [9]. An activity typically taught in electromagnetism curriculums, and pursued in makerspaces, is the construction of audio speakers. Audio speakers, found in headphones and concert sound systems, involve different physical phenomena that are invisible - such as flow of electric current, amplification and alternation of electricity, generation of magnetic fields, production of forces acting to vibrate membranes, audio waves, to name a few. These phenomena are invisible and interact with each other in complex ways, thus making the concept difficult to understand. Yet these phenomena are critically important for understanding the physics of electromagnetism. We believe that emerging technologies, such as augmented reality, have the potential to address this issue and transform STEM learning by making such challenging concepts accessible to students. Augmented reality headsets, such as the Microsoft Hololens, allow students to see virtual "holograms" in the physical world. It is therefore possible to design activities where learners can visualize and interact with dynamic representations of hidden forces (e.g., visualizing electrons, magnetic fields, light, or audio waves).

In this research we measure how collaborative learning is influenced by AR, and what features of the AR experience are causing those effects. We created an AR experience that provides dynamic visual representations of electromagnetism concepts that are aligned to a physical interactive system. We investigate how the presence or absence of such representations influences collaborative learning, while keeping our experimental conditions as similar as possible. This paper contributes to a richer understanding of the benefits and detriments of AR technology in educational settings, as well as understanding of which AR design features are influencing the observed effects, by investigating the following research questions:

- RQ1: How does AR impact knowledge *learning*, especially transfer?
- RQ2: How does AR impact knowledge *exchange* between collaborators?

The rest of the paper is structured as follows: We first present related literature discussing augmented reality for education and collaborative learning. We follow with a description of our augmented reality system for visualizing invisible physics phenomena. We then describe our research design, including independent and dependent measures, data analysis methods, participants, and study protocol. We present quantitative and qualitative results, followed by a discussion of the findings. Finally, we conclude with some limitations, directions for future work, and conclusions.

2 Related Work

In the following sections we discuss existing research on augmented reality in education, specifically focusing on augmented reality for physics education, and relationships to collaborative learning. When people engage in collaborative learning, there are many inter-related variables that can be measured. In this research we focus on measuring how AR technology influences learning (e.g., how much collaborators learn about specific concepts and can transfer knowledge to new situations); and communication processes (e.g., how collaborators communicate and teach each other). Previous research has typically studied the effects of AR applications on these variables in isolation, and without experimentally manipulating the features present in the AR experience. In contrast, this study compares features of one AR experience, and measures these variables as collaborators learn electromagnetism.

2.1 Individual Learning in Augmented Reality

Augmented reality is a technology that expands physical experiences by superimposition of virtual content on physical objects, typically by using a projector or a headset [10]. AR applications have been used in classrooms through different platforms such as handheld smartphone applications [11], hands-free low-cost headsets such as Google Cardboard [12], and more interactive high-fidelity headsets such as Microsoft Hololens [13]. Each type of AR platform provides different affordances for learning [3], [4], [5], [6] for instance AR headsets allow for higher kinesthetic engagement through interactions with both free hands, while smartphone-based AR permits a wider audience to access educational content. In this study we used the Microsoft Hololens because of its ability to simulate complex phenomena and accurately align virtual content on physical objects, while allowing students to use their hands to interact with the learning content.

Augmented reality experiences are widely reported as being highly engaging by users [14], [15]. Users usually report feeling higher satisfaction, having more fun, and being more willing to repeat the AR experience. Interestingly, in comparisons between AR and non-AR experiences, user motivation remains significantly higher even when the AR experience is deemed more difficult to use than the non-AR alternative [16]. While research on augmented reality has detected increases in user motivation, it is unclear if these effects are due to the novelty of the experience, and it is not clear if AR has a deeper effect on potentially changing student learning.

Comparative studies have compared AR applications vs. non-AR applications (in traditional instructional approaches, such as textbooks, videos, or PC-only interfaces) in individual learners, and show that AR leads to improvement in student abilities to visualize structural phenomena [13], [17], [18], reduced cognitive load [19], improvements in motivation and self-confidence [17], [20]. However, understanding of theoretical knowledge has mixed results, with some research showing improved understanding [20], while others did not [19], [21]. In this project we further this research by contributing a nuanced understanding of the benefits and drawbacks AR representations for physics education, specifically for the context of electromagnetism education in a collaboration setting.

Electromagnetism comprises the set of concepts relating the properties of electricity to magnetic fields. It is a topic that students of all ages struggle with [7], [8], [9], [21]. Students must understand and internalize abstract knowledge that is invisible to the naked eye (such as the shape of magnetic fields and flow of electric currents) and which has no simple real-life referent (such as what voltage is, or how magnetic fields are generated from the flow of electricity). Existing studies have explored the effect of adding educational representations to physical objects in order to teach challenging electrical and electromagnetism concepts. AR representations of electricity flowing through real circuits have been researched (e.g., [19], [20], [22], along with AR visualizations of magnetic fields [23], [24], and electromagnetism concepts [21], [25], [26]. For instance, [23] revealed that junior high school students learn about magnetic fields more easily when using AR-based tools than traditional approaches, and that students were able to retain the concepts longer, indicating the value of AR visualizations for learning magnetism. Similarly, [24], [26] showed that AR helps students learn better about magnetic fields and that AR helped with critical thinking about the content, when AR visualizations were shown on physical cards. Motivational effects were reported in research such as [27] showing that learning about magnetism with screen-based webcams is highly engaging for students. Similar results were found by [28] in a quasi-experimental study where students experienced high motivation when interacting with AR physics simulations; however, when wearing AR headsets students had issues with gestures towards AR visualizations that are not anchored to real objects, indicating the importance of physical objects in AR applications. These findings suggest that AR can be a valuable medium for supporting learning in the context of physics education due to its 3D visualization potential. However, due to limitations in technology capabilities, previous research has mostly focused on using simple augmented objects (e.g., visualizations shown on flat physical cards, or visualizations floating in space) instead of augmenting real 3D objects. Our research adds to the domain of AR physics education applications, by contributing a system for learning electromagnetism concepts overlaid on real objects such as sound producing speakers. Furthermore, previous research has mostly focused only on individual learning rather than learning through collaboration. In this research we contribute an investigation of how learning occurs in the context of a collaborative setting between pairs of students learning electromagnetism.

2.2 Augmented Reality as Medium for Communication and Knowledge Exchange

While the effects of AR experiences on cognition and learning have been studied, there is relatively less research focused on understanding the impact of AR headsets on the dynamics of co-located collaboration. Previous research projects have focused on designing AR infrastructures that support social interactions [29], for example by creating a variety of features for users to be able to communicate and manipulate the same 3D augmented content in collocated settings [30] or allowing remote experts to inhabit a physical space with a collaborator [31]. In this research we study the context of students collaborating in a collocated activity.

In situations where students collaborate to explore a physical artifact, imbalances of participation can negatively affect social group work [32], due to unequal access to resources, unequal domain knowledge, or dominant behaviors. When a resource is limited among team members, one person tends to dominate the interaction, creating imbalanced participation [33]. In such contexts, other participants may simply follow along the dominating partner, leading to decreased learning and poorer collaboration (e.g., "free rider effect"; [32]. In situations where collaborators do not contribute equally, this typically results in lower learning gains [34], [35]. Successful collaboration between strangers involves the interactive and iterative process of building a common ground [36]. Building a common ground ensures that small groups share a common definition of the terms used and continuously engage in shared meaning making [37]. To do so, team members need to externalize their thought, articulate their thinking, clarify points of confusion, build on each other's ideas and co-construct ideas [38]. This type of collaboration, however, breaks down when there is unequal participation. Unequal participation is influenced by multiple factors including unequal personal interest and initiative, unequal knowledge relevant to the activity, or unequal ability to control the activity.

Shared interfaces, such as tangible objects and augmented reality, have been proposed as methods to balance participation, as each user has shared physical access to the learning content [33], [35], especially when such interfaces allow participants to have shared control and awareness of information [39], [40]. It has been argued that dominance behaviors can also be balanced by augmented reality experiences, since group members using AR typically have access to shared visualizations, and this decreases the likelihood that person controls the group resources [41], [42]. We contribute to this research agenda by studying how collaboration aspects of communication, dominance, and knowledge imbalance are impacted by the presence of educational AR representations, presented as holograms on physical artifacts. On one hand, the presence of AR virtual representations could help balance collaboration by making control and information available to the different types of collaborators; on the other hand, the use of AR headsets may inhibit participant communication, for instance by blocking communication through nonverbal cues transmitted facial expressions. In this research we investigate these factors by comparing communication and teaching behaviors in groups who experience AR information vs. those who do not.

3 Materials and Methods

3.1 Apparatus

We explored how the presence of augmented reality educational features influences metrics of learning and knowledge transfer under two main conditions, employing quantitative and qualitative methods to study differences between conditions. Our apparatus consists of an interactive hardware system that replicates an audio speaker and displays AR visualizations (Fig. 1). The speaker functions by receiving electricity from an audio source, amplifying

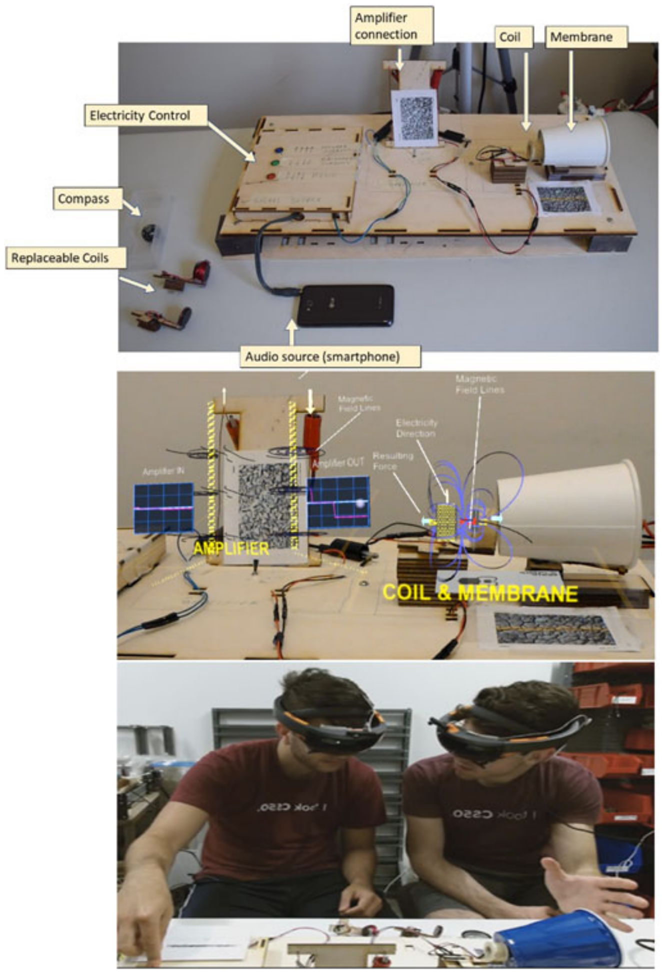

Fig. 1. The augmented reality speaker system. Top: physical speaker system. Middle: AR view of the magnetic fields around the coil and the magnet that are generating the sound waves. Bottom: two users interacting with the speaker activity using AR headsets.

the electricity before passing it through a coil of wire; adjacent to the coil is a diaphragm membrane with an attached magnet, which creates sound by vibrating at the frequency of electricity in the coil. Participants can push buttons on the control board to play music from a smartphone or send constant forward or backward current through the system. Participants can also control the distance of the diaphragm membrane, change the type of coil used, and adjust the amplification. Interactions with the hardware activates AR visualizations (Fig. 1 middle) of electric current (yellow electrons moving along physical wires, charts showing voltage), magnetic fields (curved lines around the coiled wires and magnets, and coaxial planar rings around straight wires), and sound waves (green semi-spheres).

3.2 Conditions

Pairs of study participants were randomly assigned to one of two main experimental conditions varying on the presence or absence of educational AR representations (non-educational AR: "Non Ed.AR", and educational AR "Ed.AR"). Since previous literature identified novelty as a strong effect of AR technology on learners, within the "Non Ed.AR" condition we ensured that half the groups did not wear a Hololens device at all ("Non Hololens"), while half wore the

TABLE 1
Information Representations Presented to Each Condition. (X = Present At All times. D = Presented After Specific Delay)

Features	Non Educational AR		Educational AR	
	Non Hololens	Hololens Simple	AR Layered	AR Full
Hololens device		X	X	X
System interactivity	X	X	X	X
Labels & outlines (printed)	X	X	X	X
Label & outlines (AR)		X	X	X
Sound visuals (AR)		X	X	X
Magnetic field visuals (AR)			D	X
Electricity visuals (AR)			D	X
Electromagnetism poster (AR)			D	X
Electromagnetism poster (printed)	X	X	X	X

device but only saw basic AR information such as holographic labels on major components ("Hololens Simple"). Furthermore, previous research suggests that presenting complex information at once may increase cognitive load and decrease learning; thus, within the "Ed.AR" condition, half the groups were exposed to AR information in timed layers, while the other half saw all the AR information at once ("AR Layered" and "AR Full"). The conditions and their features are listed in Table 1, and Fig. 2 shows views from each condition. For the current paper, we focus our analysis on the top-level grouping (Ed.AR vs Non Ed.AR), and only discuss the secondary level when appropriate.

Presence of Educational AR: Participant dyads were randomly assigned to conditions in which educational AR representations were present (Ed.AR) or not present (Non Ed. AR). Participants in the Non Ed.AR condition could interact with the physical system; furthermore, all conditions had access to a physical poster (Fig. 3) that explained electromagnetism concepts, had labels showing the function of pieces of the physical system, and had access to a compass for measuring magnetic fields. Participants in the Ed.AR condition had access to the same information and

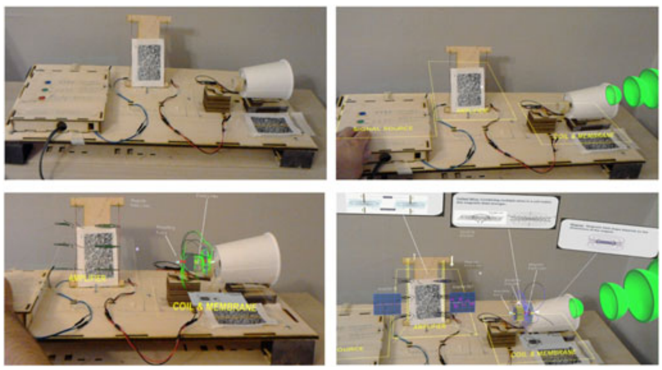

Fig. 2. Views of the system under different experimental conditions. Top Left: View without Hololens headset ("Non Hololens" condition). Top Right: Hololens with basic AR, virtually displaying apparatus areas and sound waves ("Hololens Simple" condition). Bottom Left: AR view including magnetic fields in green (visible for a time during the "AR Layered" condition). Bottom Right: AR view including magnetism, electricity, and poster images ("AR Full" condition).

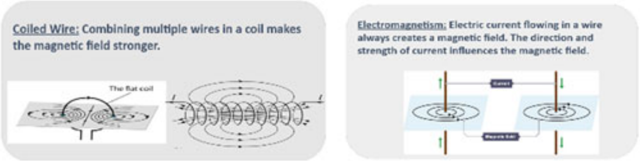

Fig. 3. Printed pages shown on the physical poster in front of the participants.

interactions, but could also see interactive visualizations of magnetic fields, electron flows, and electricity graphs.

Presence of Basic AR Hardware/Software: From existing literature and pilot studies we determined that participants become excited about wearing a Hololens device and seeing augmented reality visualizations even when educational information is not presented in AR. The effect of exposure to basic AR hardware/software was compared through two experimental conditions ("Non Hololens", "Hololens Simple"), both of which were under the category of No Educational AR. Participants in the "Non Hololens" condition did not wear a Hololens AR device, and thus only had access to the physical materials available to all other participants. Participants in the "Hololens Simple" condition wore the Hololens device and saw limited AR visualizations which only included rectangular outlines of the major system components (which were also marked in the physical space), and 3D visualizations of sound waves being emitted from the speaker.

Delayed Presentation of AR Information: The educational AR groups were split into 2 subgroups, in which the presentation of AR visualizations was either presented all at once, or sequenced by a timer. These two modes of presentation were selected because previous work suggests that presenting increasingly complex representations facilitates learning, while presenting all the information at once may instead increase cognitive load and decrease learning [43]. Participants in the "AR Full" group experienced all the AR visualization layers from the start. Participants in the "AR Layered" condition wore the Hololens device, but for the first 10 minutes of the activity they only saw visualizations similar to the "Hololens Simple" group (i.e., visualizations of sound waves, and AR labels on system components); after 10 minutes they saw the AR layer of magnetic fields; after 15 minutes they also saw the AR layer of electric current; and after 20 minutes they saw the same information available on the poster added into the AR experience.

3.3 Measures

We investigate the impact of these factors on learning and collaborative knowledge exchange, through the following measures:

3.3.1 Learning

Participants' learning was measured using relative learning gains based on pre- and post-tests. Relative learning gains is a measure of the relative improvement that occurred between pre-post test scores, calculated as the ratio between actual improvement and the total amount of possible improvement: (post score – pre score) / (max achievable score – pre score). This metric accounts for the knowledge that each participant has coming into the study, and the fact that a participant's score will not increase as much when they already know a lot. The scores are calculated on a learning test that contained multiple-choice and open-ended questions measuring several aspects of conceptual knowledge. For coding open-ended questions, a coding scheme was created; it included separate codes for each question, and examples for when the codes apply. Two researchers coded open-ended questions, each focusing on separate test questions; each question was graded by only one researcher. Learning metrics are listed in Table 2 and described below.

TABLE 2
Learning Metrics Measured Through pre- and post-Activity Tests

Conceptual Knowledge	Example Question
Shapes of Magnetic Field	Draw the shape of a magnetic field around a coiled wire.
Near Transfer	One day while you are hiking through nature, you accidentally drop your iron keys into a hole in the ground. Could you retrieve your keys using only the battery and soft long wire you carry in your backpack?
Farther Transfer	Is it possible to build a motor that is moved through electric signals ? If yes, explain how.
Sequential Reasoning	<Coded if open-ended answers followed narrative sequence describing components and including words such as "first", "second", "then", .. >
Amplifier effect on Electricity / Mag Field	In the charts below, plot the current in the wire before and after the amplifier.
Rel. between Electricity and Mag Field	If the direction of electric current is suddenly inverted, the magnetic field: (a) Does not change (c) Inverts (b) Magnifies (d) Weakens
Rel. between Movement and Electricity	If the direction of electric current is suddenly inverted, the speaker membrane: (a) Is pulled closer (c) Is pushed away (b) Does not move (d) Moves, but the direction cannot be determined
Rel. between Movement and Mag Field	If the magnetic field is suddenly inverted, the speaker membrane: (a) Is pulled closer, (c) Is pushed away, (b) Does not move, (d) Moves, but direction cannot be determined

Participant understanding of *magnetic field shapes* was measured through multiple-choice questions and open-ended drawing questions (Fig. 4). Understanding of the *amplifier's effect on electricity and magnetic fields* was measured through one specific question and through coded open-ended questions (Fig. 4). Multiple-choice questions and coded open-ended questions (such as *"How is electrical energy turned into sound inside the speaker?"*) measured understanding of the relationship between *magnetic field and movement*, *electricity and movement*, *electricity and magnetic field*. A large number of

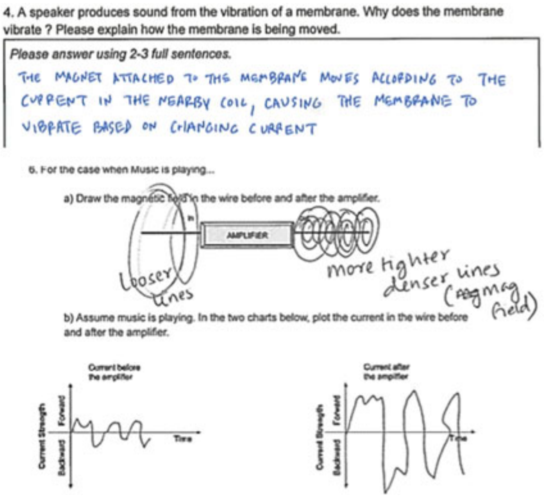

Fig. 4. Examples of questions from the learning test.

responses included a narrative which explained the connection between different components as a sequence rather than directly explaining the core physics phenomena driving the speaker. Such *sequential reasoning* can indicate shallow understanding of learning content that leads to student difficulties in understanding electronic circuits and [44]. Two *transfer questions* were used to measure participants' ability to apply knowledge to other situations within the domain of physics. Near transfer was measured through the question: *"One day while you are hiking through nature, you accidentally drop your iron keys into a hole in the ground. Your keys are made of iron, and iron is attracted to magnets. In your backpack, you have a soft long wire and a square battery. Could you retrieve your keys using only these materials? Please explain."* To answer this question, the learner must propose a solution similar to the observed speaker system, in which electricity must be passed through a coil in order to attract the iron keys. Farther transfer was evaluated through the question *"Is it possible to build a motor that is moved through electric signals? If yes, explain how."* The solution to this question requires applying knowledge of electromagnetism to a more different situation, whereby electricity passing through a coil of wire would be used to magnetically push and pull a spinning axle, that in turn creates rotational motion.

3.3.2 *Knowledge Exchange*

We performed qualitative analysis of participant communication, to better understand how knowledge exchange differs between conditions involving AR educational representations vs. those that do not. In order to have a highly contrasting set of cases, we used 8 groups from two opposing conditions: 4 groups from Non-Hololens condition not containing AR, and 4 from the AR Full condition. To ensure balanced representation of learning within each of these two conditions, half the groups represented high learning gains and half represented low learning gains (from the top quartile and bottom quartile, respectively). This selection allowed us to observe differences due to the effect of AR representations, as well as observe differences between collaboration in high and low learning.

A coding scheme for understanding communication was constructed through iterative bottom-up coding, resulting in dimensions such as the ones in Table 3. For the purpose of this paper, we focus the analysis on interactions, where at least one of the two participants tries to teach the other participant a physics concept through explanations or clarification. Each of these dimensions were evaluated for 30-second time intervals of participant collaborations; this time period was determined suitable for capturing these dimensions. To generate the results, research study videos from the eight participant sessions were split into 30 seconds time frames and assigned one or more codes from the coding scheme. If multiple codes could be assigned during a 30-second observation frame, the code which took the largest amount of time was recorded. Inter-rater reliability of Cohen's kappa of 0.8 was reached by two researchers coding 20% of videos, which implies substantial/almost perfect agreement. Dimensions of the coding scheme are detailed in Table 3.

TABLE 3
Qualitative Codes and Definitions

Code	*Definition*
Communication Medium: The method of non-verbal communication.	
Deictic gestures	Gestures for directing attention, coded when a participant is pointing or using gestures to make the other participant shift his/her attention to a certain location.
Iconic gesture	A symbolic gesture when a participant is using his/her hand to mimic a visual representation.
Self generated drawing	Recorded when one participant is drawing on a paper to support his/her explanation.
Communication Aids: The tool used for communication.	
Wall poster	Communicate while looking at the wall poster.
Compass	Communicate while using the compass.
System	Communicate while using the system.

3.4 Participants

Participants were recruited from the study pool of a university in the northeastern United States. Participants who signed up for a study session were required to not know each other, have no significant prior physics knowledge, speak English fluently, have at least a bachelor's degree, wear no bifocal glasses (due to the limitations of our AR device), and be less than 40 years of age. Prior to participation, participants were provided with information about the procedure and informed consent was obtained. Pairs of participants were randomly assigned to one of the four experimental groups. We recruited 15 participant pairs for each condition (N = 120 individuals, N = 60 dyad pairs). For the analysis, we removed sessions in which technical issues were encountered, and removed outlying participants whose pretest score was beyond 2 standard deviations from the mean, which resulted in 14 pairs in each of the four experimental conditions (N = 112 individuals, N = 56 dyad pairs).

3.5 Procedure

At the beginning of each study session, each group was randomly assigned to one of the 4 study conditions. Participants were asked to introduce themselves to each other, then individually completed a paper-based pre-test which measured the Learning Metrics, lasting 15 minutes. After the pre-test, each participant was provided with a sheet of paper containing basic information about concepts relevant to the study activity and were asked to indicate once they are done with reading. The paper contained introductory information about "What is electricity?", "What are magnetic fields?" and "What are sound vibrations?", and was typically read under 4 minutes. Participants were then paired with their partner and presented with the speaker system. For the groups using the Hololens AR device the participants were then equipped with the device. All groups watched a 5 minute video provided an overview of the components of the system (listed in Fig. 1 top), and how to interact with them (i.e., how to slide the speaker membrane, how to push buttons that control the electricity, how to turn on/off the amplifier, how to change the wire coils, and how to use the physical compass to measure magnetic fields). Afterwards, participants were told they have 30 minutes to answer questions on a worksheet while exploring the system. Participants who wore the Hololens device saw visualizations according to their condition, as described in Table 1 and in the Independent Variables section. After the 30 minutes activity, participants were individually asked to complete a paper-based post-test similar to the pre-test, lasting 15 minutes. The study concluded with a debriefing indicating the study purpose; during the debrief for the Non Ed.AR conditions, participants were also shown the Ed.AR visualizations which they did not see during the study.

3.6 Data Analysis

To answer RQ1, impact of AR on learning, we analyzed the learning metrics in relation to the two main experimental groups, aiming to perform T-tests when parametric assumptions were met, and non-parametric alternatives (Wilcoxon–Mann–Whitney and Wilcoxon Signed Rank tests) when parametric assumptions were not met. To answer RQ2, impact of AR on knowledge exchange, we performed qualitative analysis of teaching and communication behaviors.

4 Results

4.1 RQ1: How Does AR Impact Knowledge Learning, Especially Transfer?

The effect of AR on knowledge learning and transfer are presented in Fig. 5, and statistical information in Table 4. Our final dataset did not meet parametric assumptions of normality (tested through Shapiro-Wilks test on each metric, $p<0.05$), thus only nonparametric statistics were used. Participants in Ed.AR groups had statistically higher relative learning gains than compared to Non Ed.AR groups (Table 4) on their ability to identify and draw magnetic field shapes, their understanding the relationship between electricity and magnetic fields, and on answering the near transfer question. On the other hand, participants in Non Ed.AR groups had statistically higher relative learning gains than compared to Ed.AR groups on their ability to understand the relationship between magnetic fields and movement, and were more likely to exhibit sequential reasoning. Within the sub-groups of Presence of Basic AR Hardware, and Delayed Presentation of AR Information, we did not detect between-group statistical differences; however, it is worth highlighting that the sub-groups are relatively small ($N = 14$) thus our analysis lacks statistical power, which could be achieved with a larger sample size.

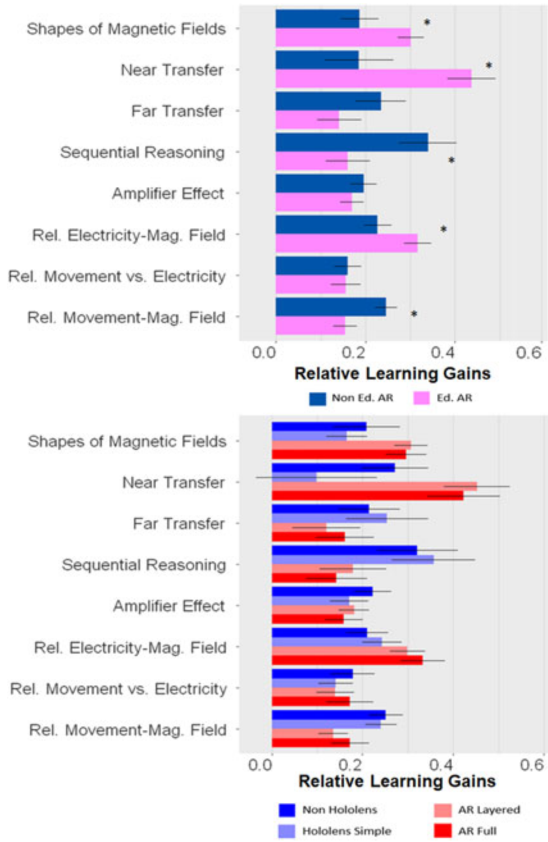

Fig. 5. Group differences in relative learning gains (scores 0-1 computed from pre-post tests as detailed in Section 3.3) between the main experimental groups (top), and between the four experimental subgroups (bottom). Bars = standard error. Stars = sig. ($p<0.05$).

4.2 RQ2: How Does AR Impact Knowledge Exchange Between Collaborators?

In the quantitative analysis we determined that the presence of AR educational representations has effects on participant learning and transfer. However, it is not clear how these effects are generated, and how AR information is mediating the knowledge exchange between participants. To further understand this, we qualitatively analyzed the 8 video sessions (4 Ed.AR, 4 Non-Ed.AR; each condition containing 2 high-learning groups and 2 low-learning groups) which ranged between 27-30 minutes. In total, 489 30-sec. segments were coded, accounting for 4 hours of video. One researcher coded 100% of the videos, and for inter-rater reliability another researcher coded 20% of each video. Cohen kappa of 0.8 was reached for inter-rater reliability, implying substantial/almost perfect agreement. The qualitative findings are presented below.

AR groups finish quicker and have easier access to information: Generally, participants in the AR condition finished the activity 14% faster than the participants in the non-AR condition. In the qualitative analysis we observed the AR groups communicated that they were finished with the activity after roughly 26 minutes, while the non-AR groups typically continued the activity until the 30 minute time

TABLE 4
Main Group Statistics and Statistical Results, for the Relative Learning Gains Metrics. Stars = Sig ($p<0.05$)

Metric	Non Ed.AR M (SD)	Ed.AR M (SD)	Statistical Test
Shapes of Magnetic Fields	0.19 (0.32)	0.30 (0.22)	W = 1940, p = 0.047 *
Near Transfer	0.19 (0.56)	0.44 (0.40)	W = 1920, p = 0.009 *
Farther Transfer	0.23 (0.42)	0.14 (0.36)	W = 1380, p = 0.364
Sequential Reasoning	0.34 (0.48)	0.16 (0.37)	W = 1290, p = 0.030 *
Amplifier Effect	0.20 (0.22)	0.17 (0.20)	W = 1520, p = 0.635
Relation: Electricity vs Magnetic Field	0.23 (0.24)	0.32 (0.23)	W = 1950, p = 0.044 *
Relation: Movement vs Electricity	0.16 (0.23)	0.16 (0.25)	W = 1570, p = 0.880
Relation: Movement vs Magnetic Field	0.25 (0.19)	0.15 (0.20)	W = 1140, p = 0.007 *

limit. High-learning groups in both conditions spent more time interacting with the system than low-learning counterparts who tended to finish earlier. In Table 5 we illustrate this phenomenon of AR participants finishing more quickly. This example illustrates how AR and non-AR participants react differently to the same prompt: low AR group participants pause and stare at the AR system, and both participants observe the direction of the cup then come up with their assumption on the relationship between electricity-movement-magnetic fields, and do not make effort to explore the questions more deeply. In contrast, for the non-AR group it takes longer to discuss the same question, using lengthy discussions with various iconic hand gestures.

AR facilitates peer teaching through shared representations: While observing study groups, we saw differences in how participants explained concepts to each other. We found that in the AR condition, participants spent less time in the activity for teaching each other concepts, compared to the non-AR condition. Specifically analyzing the use of aids in teaching, we found that AR participants primarily taught each other while using the system, not while using other tools such as compass or poster. In the non-AR condition, participants taught using the various aids (listed in order of preference): using compass, using the system, using the poster, or using other methods such as drawings (Fig. 6 top). Aside from the differences in tools used as aids to teach, the participants in the conditions also utilized different communication methods to teach (Fig. 6 bottom): the AR participants mainly used deictic gestures, few iconic gestures and no drawings. In contrast, non-AR participants used much less deictic gestures, but generated more iconic gestures and more drawings. Table 6 shows an illustration of this, specifically how an abstract concept (magnetic polarity) is taught more directly with AR. In the non-AR group, Participant 1 slowly taught Participant 2 how to read polarity from a compass, whereas in the AR group Participant 1 was able to instruct the other participant to simply look at the polarity directions provided in AR. These results suggest that the AR system provided representations to teach more effectively, skipping the process of acquiring representations from other aids or communication methods needed by the non-AR groups.

5 Discussion

This study highlights how different aspects of collaborative learning are influenced by the presence of augmented reality. In particular, this study adds to the body of work that has investigated the unique affordances of AR interfaces for learning [3], [4], [5], [6]. In the following sections we reflect on how AR influences the different aspects of collaborative learning in positive or negative ways, and provide some explanations of the possible underlying mechanisms driving these effects.

5.1. Positive Impacts

The presence of AR features had the effect of improving learning and facilitating collaboration. AR educational

TABLE 5
Quotes From Participants in a Low Learning Gains AR Group vs. a Low Learning Gains non-AR Group

AR Group	Non-AR Group
[P1 and P2 taking turns to press forward/backward buttons and look at the electromagnet with superimposed AR magnetic field] P1: “Oh! It’s like the direction is either pushing it away or pulling it closer” P2: “Yeah” P1: “The strength when pushing it away is less” [P1 changing the magnitude of the amplifier and looking at the AR amplifier graph] P2: “When the current is weaker, the impact on the membrane of the cup and the magnetic field is smaller” P1: “Yeah” P2: “I don’t know where to add on the paper” P1: “I think it’s all there” [P1 pointing to their existing answers on the worksheet] [Both sitting silently, then chatting on irrelevant topics]	P1: “Is the music linked to the current, so the stronger the current, the stronger the music is?” P2: “Yeah, kinda, So the music is like, little tiny current signals like saying push pull, push pull, modulating. And then it gets amplified from pushing like this, to pushing like that” [P2 using an iconic hand gesture showing different strength]. “The more windings you have, the stronger it gets. So you are shaking this magnet at a very specific pace, which then vibrates and makes sound” [P1 looking at P2 while explaining and making iconic hand gestures] P1: “Do you mind answering the question, so the stronger the current, the greater amplification we hear from the cup?” [Adding answer to the question that they previously skipped, while continuing to talk about the activity]

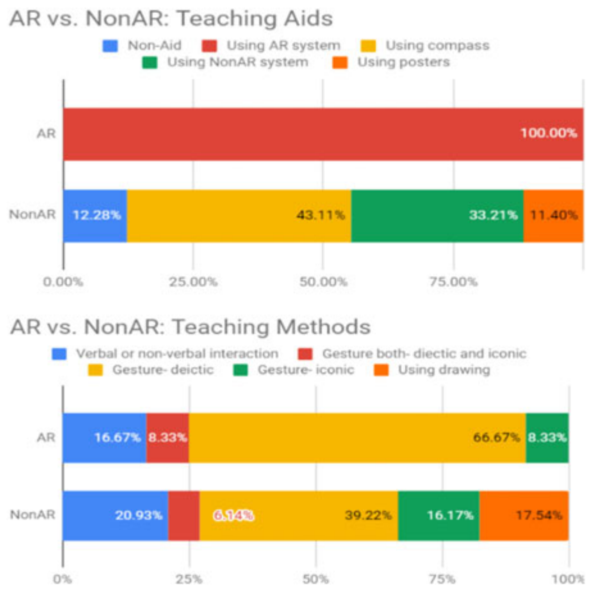

Fig. 6. Percentage of time from the total teaching time spent with specific aids (top) and specific methods (bottom).

representations had the effect of increasing learning gains. Participants who saw AR representations of electromagnetism were significantly more effective in developing understanding of the invisible structures of magnetic fields, understanding the connection between electrical currents and magnetic fields, and transferring knowledge on how to construct electromagnets. The educational AR groups differed on several factors which may explain these learning effects, including: the availability of additional AR-based representations, the alignment of the physical components to their virtual representations, the dynamic nature of virtual representation and the aesthetically engaging nature of the visualizations. Users could concurrently observe the direction of electricity while watching magnetic field shapes, thus experiencing concurrent exposure to two learning concepts (magnetic field shapes and their relationships to electricity and magnetism), which would explain significant learning differences in these topics. Providing such dynamic representations aligned in a physical context through AR can allow learners to easily keep track of relevant information while exploring the dynamic nature of relationships between variables. Previous research has shown that AR experiences can be beneficial in increasing student engagement, although this effect may be due in part to technology novelty or due to the type of AR representations visible to users [14], [15]. In the current study we separated the effects of novelty from the presence of educational AR representations (Non-Hololens and Hololens-Simple groups), and found that, when educational AR representations were absent, the learning gains were not significantly impacted by the presence of AR technology and its associated novelty; yet, learning was significantly lower than groups having access to educational AR representations.

Collaboration was also impacted by the presence of augmented reality, whereby AR enabled groups to finish more quickly, access information relevant to the learning task, and ground their communication in the visual representations. For collaboration across groups in general, we found that groups without educational AR representations showed weaker time management and tended to run out of time. The AR representations were useful for communication and task completion, as groups without AR had a harder time understanding the system and spent more time generating their own representations (for example by drawing). This indicates that AR can potentially improve collaboration. A reason for this may be that AR representations facilitate grounding [36]. AR can increase availability of common information to both participants, which can allow participants to communicate points of confusion or curiosity more easily, by referring to the existing AR representation. Referring to representations might also benefit the more knowledgeable participants when teaching their peers, which can increase participation from passive participants. This is in line with prior findings that have found that AR systems can support social interactions [29] (e.g., by allowing more access to learning material [30]). Our results further suggest that improved grounding can also facilitate content-related peer explanations, which is an important learning mechanism in small groups [45].

5.2. Negative Impacts

Beyond these benefits, there were some negative effects observed. Having AR educational representations was detrimental for learning of some concepts. The groups that had AR

TABLE 6
Quotes From Participants in an AR Group vs. a non-AR Group While Teaching

AR Group	Non-AR Group
[Both looking at the magnetic field AR] P1: “This button pushes the magnet in and out. . .” P2: “Um hm” P1: “Because the magnetic field changes, you see? It’s inverted. It changes between north and south.” [P1 referring to the AR magnetic field] P2: “Yea” P1: “So it causes the push and the pull of the magnet, right? P2: “I guess.” [P1 looking at the AR magnetic field while explaining] P1: “The magnetic field is inverted all the time. In order to have music, they change very quickly between forward and backward.”	P2: “How do I use this?” [P2 trying to use a compass] P1: “This is north, [P1 moving a compass to the other end] this is south. Let me try one second. The moment you come outside of the membrane, it’s north. When it is near the membrane, it is south. So north to south, that’s how the magnet direction goes.” [Using compass then iconic hand gesture] P2: “How about this part?” [P2 pointing to the coils] P1: “This is where they produce electricity current, it starts from the magnetic membrane, this is where the south and north pole comes in.” P1: “When I push a forward current, it starts at south pole and ends at north pole. And the backward current is north to south.”

educational content scored lower on understanding the relationship between magnetic field and forces on physical movement. Participants who wore the Hololens device (even those groups which never saw AR educational representations) tended to gloss over the physical compass or poster. The low use of the compass tool is partly explainable by the availability of the magnetic field representations, which removed the need for users to measure magnetic fields. Overall, these findings indicate that AR participants focused less on physical materials and tactile feedback (i.e., the feeling of movement caused by magnetic field forces). This was likely caused by highly stimulating AR visualizations, which may have prevented learners from focusing on more kinesthetic information. A related detrimental effect was that participants who saw augmented reality educational representations seemed to exhibit 'tunnel vision', whereby they spent the majority of their time utilizing the AR system visuals without leveraging other aids available to them (e.g., wall poster, compass). This contrasts with the Non Ed.AR participants who frequently used external aids. This can be explained by the availability of information in the AR visualizations, as well as by the tendency of AR experiences to capture user attention [5]. This attentional focus may explain why the AR participants showed better understanding of concepts illustrated within the AR system, such as understanding magnetic fields, whereas participants without educational AR showed better understanding of kinesthetic phenomena such as relationship between movement and magnetic fields, which benefited from focusing on kinesthetic information. It is possible that AR participants focused strongly on the visual experience and ignored physical aids, while the Non Ed.AR focused on physical aids, in turn increasing their awareness of physical effects in the learning experience. Because AR users' attention is so strongly drawn to "holograms", AR experiences might be a double-edged sword. On one hand, spatial-temporal contiguity affordance of AR [46] can help participants comprehend complex visual representations. At the same time, it can also impede participants from focusing on other physical tools or learning about non-visual aspects of the system. To address this, AR experiences can be designed to include instructions that direct users' attention to non-augmented components, for example "Try the compass!".

We found that some participants had trouble understanding the AR representations. This may occur when participants lack basic background knowledge of the concepts taught: for example, one issue was that users did not know how to make sense of the magnetic field since they had no prior exposure to this type of representation. This led to problems such as interpreting field strength based on the size of the magnetic field lines rather than their density. Contextual information needs to be provided with the AR application, to ensure that students can interpret the different kinds of representations used in the AR visualizations, as improper interpretations can lead to development of misconceptions. Furthermore, some participants using AR may have gained a false sense of understanding of concepts conveyed by the system, because the information provided allowed participants to finish answering more quickly. AR participants communicated earlier that they were finished with the activity than NonAR participants, and the effect appeared stronger for AR groups with low learning gains than groups with high learning gains. This suggests that when participants have easily accessible information through tools such as AR, it may create a false sense of confidence, causing students to learn less because they stop engaging with the learning content earlier, and potentially think less critically about the underlying concepts. In sum, our study provides a more nuanced understanding of the benefits and drawbacks of AR representations compared to prior work: we identified factors that positively affect learning (e.g., co-located representations, easier access to resources, better grounding) but also negatively affects learning (e.g., tunnel vision, overlooking kinesthetic feedback). Further research can investigate when presenting AR-based information is useful or detrimental to learning.

5.3 Limitations

We acknowledge several limitations present in our study. The sample size limited the statistical power to detect differences between the 4 secondary conditions. While our findings indicate differences between primary groups (Ed.AR vs Non Ed.AR), further research is required with larger sample sizes to investigate other effects that may be present in the subgroups. Furthermore, our qualitative analysis of communication methods and tool use was applied to only 8 groups; the results should be replicated to confirm the observed behaviors occur in larger scales. Furthermore, the activity used in this study was of short duration (30 minutes) and closed-ended, limited to specific interactions that could be monitored by the system. The technological system developed for our study constrained the depth of interactivity in the educational experience, as the AR system could not easily track the movement or states of physical objects, thus restricted opportunities to create simulations that accompany more open-ended inquiry. It is unclear how the currently observed effects would transfer to more open-ended activities, and to activities that are integrated in classrooms for longer periods of time such as hours, days, or weeks. It is expected that the effects of novelty would disappear as students become familiar with the technology, and it is possible that the observed tunnel vision and attentional issues observed would disappear as students have more time to explore the system, however it is possible that negative effects would appear such as an increase of technology dependence, increased misconceptions, or increased fatigue. Future research should investigate the use of more open-ended electromagnetism activities where participants can interact in open-ended activities while creating different configurations of electronics, magnets, membranes, and electromagnets. Another limitation of AR headsets is that they cover participants' faces, thus reducing ability to make eye contact or communicate using nonverbal emotional expressions. Although our study did not detect detriments in collaboration caused by AR headsets, future research should investigate these differences in other contexts where nonverbal communication may contribute to successful collaboration. Additionally, the current scale of the study apparatus was small, making it easy for participants to remain in close proximity and point with their finger at specific objects; however, if the study activity takes place over a larger space where participants cannot easily touch all objects, it is expected that collaboration would be impacted due to reduced ability to see other participants' actions. It is also important to acknowledge that prolonged collaboration may cause participants to experience eye and neck fatigue from using the AR headsets for prolonged periods of time, and should be tested in future studies. Finally, we acknowledge that participant selection and variations in pre-existing knowledge introduced bias in our study results. The participants were selected to have a bachelor degree and be less than 40 years of age. It is expected that participants beyond that demographic range will have different reactions to the activity, due to differences in exposure to physics knowledge and technology. Furthermore, within our participants sample, we requested participants to have minimal knowledge of physics, but we observed a range of pre-existing knowledge. In the analysis we accounted for this by calculating learning gains through relative learning gains, a metric which accounts for differences in pre-test knowledge, and by qualitatively analyzing participants grouped by their pretest knowledge. However, it is expected that such variations influence the reliability of our results, and future studies should investigate how previous knowledge, as well as previous technology exposure, influences participants' learning and collaboration with AR technologies.

6 Conclusion

In this study we analyzed learning and collaboration in dyad pairs as they experienced an AR system for learning about electromagnetism. We found that, in this context, augmented reality was generally beneficial for both learning and collaboration. AR participants learned more about visual concepts but less about non-visual content, they stopped exploring the system quicker than NonAR participants, used less aids in exploration and teaching, and spent less time teaching their collaborators. Overall, AR representations improved time management, learning of structural concepts but reduced learning of physical concepts. AR also helped collaborators communicate and transfer knowledge, and enhanced contributions from less knowledgeable or passive participants. As augmented reality technology is becoming ubiquitous and begins entering classrooms, it is important that future research continues to investigate how AR technology can be supportive or detrimental to processes of collaborative learning.

Acknowledgments

We would like to thank the Harvard Decision Science Lab, and the dedicated research assistants who helped in the research data collection and interrater reliability process, including Apittha Unahalekhaka, Adam Petty, Alice Huang, Iva Markicevic, Francisca Astudillo, Yanru Wang and Tonya Bryant.

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