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# Weather observers: a manipulative augmented reality system for weather simulations at home, in the classroom, and at a museum

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This study focused on how to enhance the interactivity and usefulness of augmented reality (AR) by integrating manipulative interactive tools with a real-world environment. A manipulative AR (MAR) system, which included 3D interactive models and manipulative aids, was designed and developed to teach the unit "Understanding Weather" in a natural science course, and to bridge a formal learning environment (i.e. school), non-formal (i.e. at a museum), and informal learning environments (i.e. home). Sixty-four sixth-grade students (12–13 years old) from four classes in Taipei City were enrolled in a seven-week general studies course entitled "Natural and Life Science and Technology", and they were divided into an experimental group (31 students who used the MAR system) and a control group (33 students who used multimedia teaching resources). After seven weeks of experiments, the results revealed that integrating the MAR system into inquiry-based field study made a greater positive impact on the students' academic achievement and motivation compared to the multimedia teaching resources installed on a tablet PC. Additionally, there were two interesting findings: (1) the MAR system offered effective learning materials relative to the multimedia teaching resources and (2) manipulative aids were an effective learning tool for interactivity and usefulness of AR. Besides, there were two meaningful suggestions associated with designing and developing the AR educational system for future researchers and designers, namely make it easy to use and include manipulative aids.

**Keywords:** augmented reality; manipulative aids; evaluation of multimedia resources; bridging different learning environments; academic achievement; learning motivation

## Introduction

Museums, which are non-formal learning environments that students visit during field trips, are able to bridge the gap between in-school learning and out-of-school learning (i.e. at museum or home).[1] The difference between museum learning and school learning is that museum learning has the potential to engage students in an educational setting, stimulate their understanding, and, most importantly, help them assume responsibility for their own future learning (Gardner, 1991). Hicks (1986) pointed out that in schools, facts, and concepts are usually presented sequentially, through verbal communication, in a structured way, while in a museum, objects form the basis of a less-structured process, which engages

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the student's own interests, ideas, and experiences. There are different teaching/learning characteristics in school and in a museum but they have a synergistic relationship in training and fostering students' capabilities and knowledge (Sheppard, 1993). Museum learning is complementary and supportive, providing students with the experience of the "real thing", which encourages the acquisition of new knowledge and consolidates information already acquired; however, it is not a substitute for traditional teaching methods (Xanthoudaki, 1998).

Many kinds of museums have always been off-campus teaching spaces, where teachers or researchers design teaching activities or innovative teaching approaches (Chu, Hwang, & Tseng, 2010; Li-Der, Ching-Chao, Ming-Yu, & Chun-Yen, 2004; Lin & Lan, 2012; Sharples, Lonsdale, Meek, Rudman, & Vavoula, 2007). In addition, different kinds of museums, such as fine arts, natural history, science, and centers of interpretation, promote different kinds of learning (Donald, 1991). Moreover, museums have rich exhibition materials and their exhibition items directly relate to the modules listed in a prepared syllabus (Roberts, 1997). The characteristics of the exhibits effectively attract and hold learners' attention (Sandifer, 2003), as well as stimulate and enhance their intrinsic motivation (Allen, 2004; Flexer & Borun, 1984; Koran, Morrison, Lehman, Koran, & Gandara, 1984) through "hands-on" experimentation and "minds-on" reflection.

Mobile learning (m-learning) technology, with its characteristics of high portability, personalization, and context-awareness, is suitable for providing a communication bridge among formal, non-formal, and informal learning environments (Chan, Roschelle, Hsi, Kinshuk, & Brown, 2006; Looi et al., 2009; Wu, Lee, Chang, & Liang, 2013). Many researchers in the area of m-learning have developed many different teaching resources (such as multimedia animation, virtual reality, and augmented reality (AR)) on mobile devices to support formal, non-formal, and informal learning environments (Chen, 2011; Hwang, Wu, Zhuang, & Huang, 2011; Lally, Sharples, Tracy, Bertram, & Masters, 2012); specifically, AR is a new multimedia technology that has received attention in commercial game markets, education, and museums in recent years (Allen, 2004; El Sayed, Zayed, & Sharawy, 2011; Hsieh & Lin, 2006; Wu et al., 2013).

AR is a highly complicated system that integrates mobile computing, tracking technology, visual simulation, digital synthesis, and a human–machine interface and its characteristics include combining real and virtual environments, interacting in real time, and registering in a 3D environment (Azuma, 1997). AR provides students with an experience-based and bi-directional interactive learning environment to investigate the science phenomena that are not easy to explain through dictation, such as Newtonian laws of physics (Cheng & Tsai, 2012; Irawati, Hong, Kim, & Ko, 2008), to enhance students' memory, such as learning English vocabulary (Hsieh & Lin, 2006; Liu, Tan, & Chu, 2007), and to improve their attention and motivation (Iwata, Yamabe, & Nakajima, 2011; Sumadio & Rambli, 2010). In addition, Dunleavy and Simmons (2011) argued that AR has the potential to provide participatory, situated, and collaborative experiences that foster inquiry-based problem solving and critical thinking skills. AR is an emerging technology that allows people to interact with 3D virtual and real objects at the same time (Chen, 2006) and enables a kind of social play experience (Huynh, Raveendran, Xu, Spreen, & MacIntyre, 2009). However, only a few empirical studies (such as Chang, Chen, Huang, & Huang, 2011; Liu, Huot, Diehl, Mackay, & Beaudouin-Lafon, 2012) have investigated how to enhance the interactivity and usefulness of AR by replacing the fixed AR recognition card with manipulative interactive tools, which is a ponderable research issue.

Previous studies found that "learning by doing" has a positive effect on learning motivation, knowledge acquisition (Dewey, 1938; Kaagan, 1999), learning effectiveness (Hearns, Miller, & Nelson, 2010), and cognitive understanding (Gerstner & Bogner, 2009). Currently, however, the AR teaching resources applied in different educational fields lack the process of "manipulation" or "learning by doing" for learners. Many AR teaching/learning systems are limited to using a camera to capture physical picture cards, which generates 3D models of teaching materials. These 3D models of teaching materials vary, although the presentation of an AR system can enhance students' learning motivation and attract their attention (Bogen, Wind, & Giuliano, 2006; Liu et al., 2007), as well as improve their learning performance (Wu et al., 2013). However, students who use these AR systems are only observing the virtual teaching materials; that is, they are unable to achieve manipulative and bi-directional interaction between physical teaching objects. Based on the above considerations, the purposes of this study are as follows:

(1) To design and develop a manipulative AR (MAR) system to bridge formal learning, non-formal, and informal learning to teach climatology in the classroom, at home, and at a museum.
(2) Discover whether different learning instruments (i.e. a MAR system and a non-MAR system) make an impact on the students' academic achievement in climatology.
(3) Discover whether the students tend to learn natural science more readily using the MAR system, and, if so, whether it can be verified.

## Designing and developing a MAR system

This study adopted a QualComm AR (QCAR) software development kit developed by Qualcomm (http://www.qualcomm.com/) as the developing platform for the MAR system. The QCAR uses a markerless (no icon) recognition method, which offers very good quality in both operation fluency and visual effects. The QCAR can apply different software to develop digital games with 2D and 3D interactive objectives and content, and the procedure for developing the games is flexible because the AR recognition technology and the 3D interactive objectives and content are separate. The interactive modules and content in the system were designed and developed using the Unity3D game engine developed by Unity Technologies, a US company. The game engine is a powerful rendering engine fully integrated with a complete set of intuitive tools and rapid workflows to create interactive 3D content (http://unity3d.com/). Furthermore, the game engine focuses on the algorithm of physical characteristics, which provide better presentation outcomes, including simulated physical characteristics (such as gravity, collision, and friction) and environmental effects (such as lighting, shadows, and reflections) on mobile devices with limited resources.

### *MAR system framework*

This system was packaged as an android application package, which was conveniently installed on the Google Android Operating System 2.1 and above to meet the needs of an m-learning system. This system consisted of three main modules (see Figure 1), namely the instructional module, the system's kernel, and instructional resources.

Three sub-modules with different learning contents were designed and developed in the instructional module to bridge formal learning in school, non-formal at a museum, and

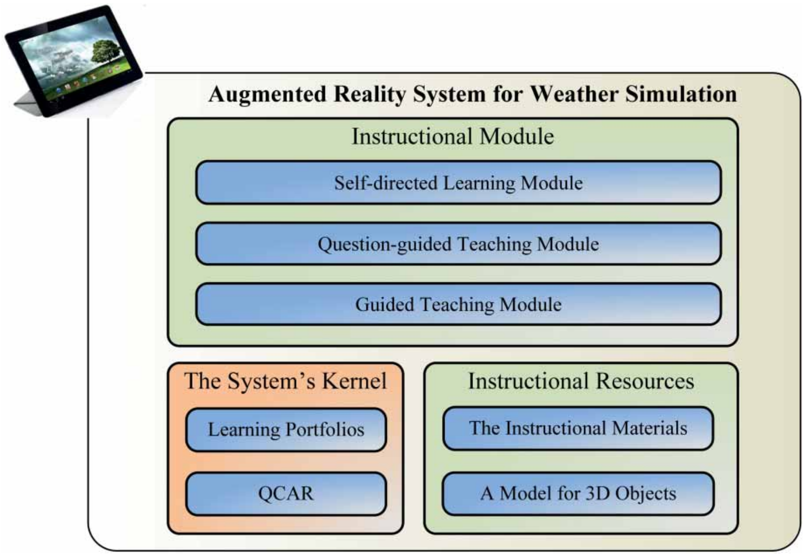


Figure 1. System architecture.

informal learning at home. These sub-modules will be described in detail in the next section. The kernel of the system mainly exhibited 3D interactive content using QCAR to detect and recognize the AR graphic cards and record the students' learning portfolios. The instructional resources included instructional materials (such as quizzes and illustrations of the exhibitions), which were presented via multimedia and 3D interactive objects related to the unit "Understanding Weather". The instructional materials and the 3D interactive objects of the MAR system were confirmed by two Nature and Science Technology teachers and the quizzes were tested and verified by an Educational Measurements and Statistics expert.

### *System interface and manipulative aids*

This study developed three sub-modules, mentioned above, as manipulative learning aids based on three different learning environments. Through the manipulation of the system and the manipulative aids, the MAR system offered students a new learning method to observe weather variations and think about weather factors. The sub-modules' interfaces and the manipulative learning aids for the different learning environments will be described in detail in the following section.

#### *Self-directed learning module at home*

This sub-module provided the students with a series of instructions about weather factors, as shown in Figure 2. After reading the instructions, the students performed the learning task associated with the weather factors. Figure 3(a) displays seven weather factor cards (i.e. sun, land, sea, air pressure, temperature, air, and vapor) as manipulative aids that can be combined to compose different weather variations. When the weather factor cards were combined in the correct sequence, the students acquired knowledge about how those factors caused weather variations (Figure 3(b)). This allowed the students to

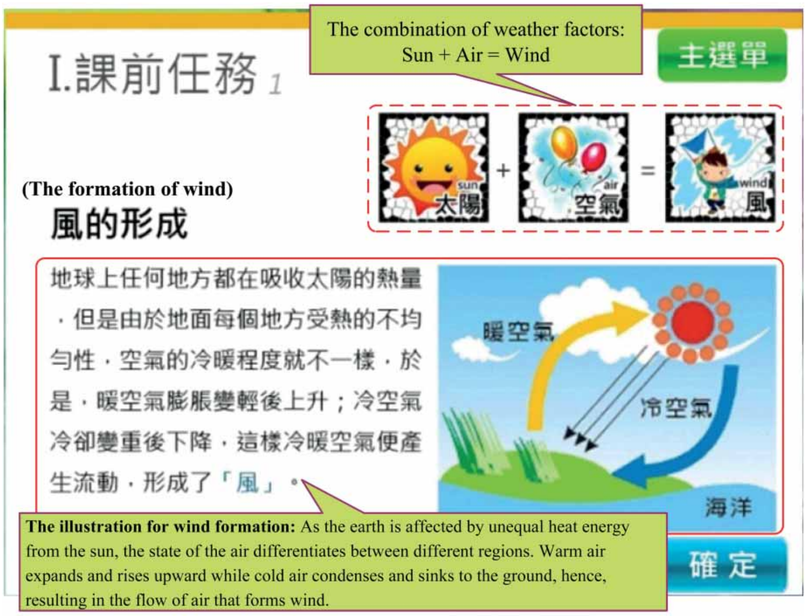


Figure 2. The instructions for weather factors.

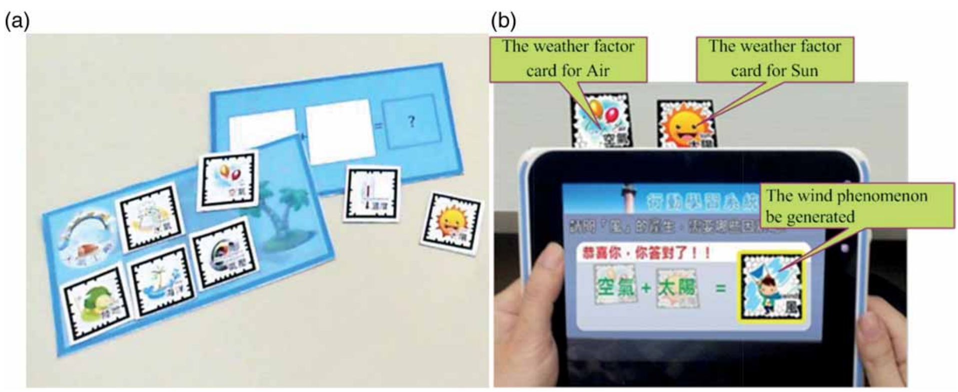


Figure 3. (a) Manipulative aids and (b) the result of a combination of weather factors.

investigate the weather factors and understand the concept of how these factors cause weather phenomena, for example, sun + air = wind.

### *Question-guided teaching module in the classroom*

In the classroom environment, this study designed and developed a manipulative weather controller. Figure 4(a) reveals that three sliders are located on the front of this controller, representing three different weather factors (i.e. sun, vapor, and temperature, respectively). The sun slider controls the weather phenomena of sunny or cloudy, so when the sun slider moves up it is sunnier, whereas when the sun slider moves down it is cloudier. The vapor

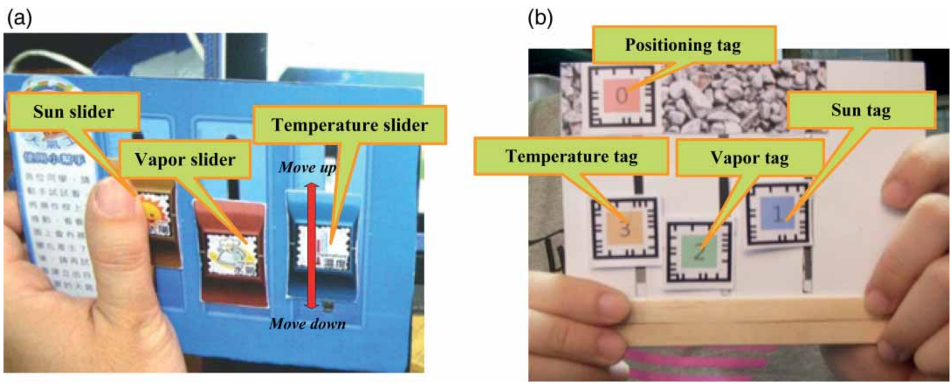


Figure 4. (a) The sliders and (b) the control tags.



slider represents the content of aqueous vapor in the atmosphere, so when the vapor slider moves up it is more humid, whereas when the vapor slider moves down it is less humid. The temperature slider signifies the temperature, so when the temperature slider moves up it is hotter, whereas when the temperature slider moves down it is colder.

To recognize the relative position of the three sliders, a positioning tag is used as a reference point to locate the positions of the other three tags (Figure 4(b)). When students manipulated the three sliders on the manipulative weather controller, the system revealed a 3D weather animation in accordance with the corresponding positions of the three tags, as shown in Figure 5. The 3D interactive objects contained two patterns: (1) an appreciable weather pattern, such as snow, sun, or clouds and the amount of cloudiness and (2) perceptible weather patterns, such as the physical strength of the wind or the temperature level. Given that the appreciable weather pattern cannot be shown directly through 3D objects, this system used substitutive 3D objects to display perceptible weather patterns. For example, we utilized the rotational speed of a windmill to reveal the physical strength of the wind.

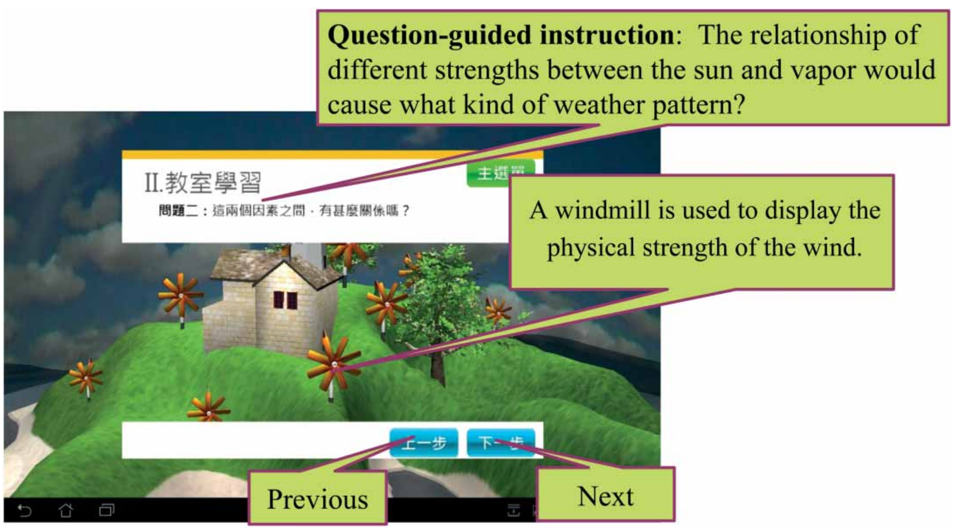


Figure 5. 3D weather animation.

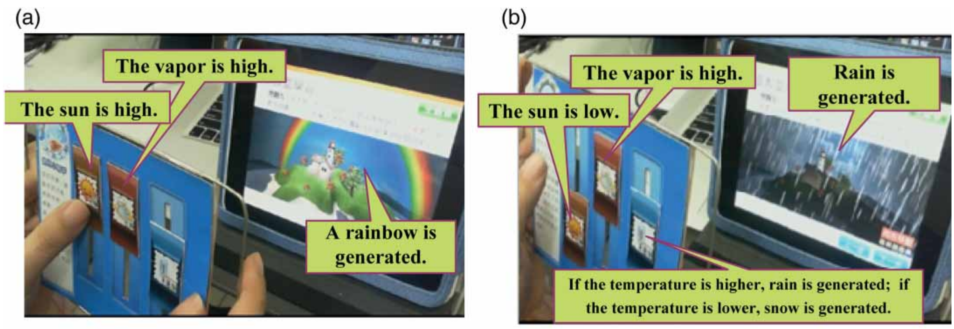


Figure 6. (a) The rainbow phenomenon and (b) the rainy phenomenon.



The students were able to generalize and deduce the elements of weather variations when they continuously adjusted the three sliders (i.e. sun, vapor, and temperature) and obtained different 3D weather animations. For example, Figure 6(a) shows that a rainbow is generated when the sun increases and the vapor increases; however, when the sun decreases and the vapor in the atmosphere increases, the system shows a rainy phenomenon, as shown in Figure 6(b).

### *Guided teaching module at the museum*

The experimental museum had five exhibition areas: understanding weather, wind, rain, clouds, and snow. In the museum environment, AR graphic cards were posted next to the exhibitions. The system generated coexistent instructional materials of virtual objects and current exhibitions when the students used a tablet PC to photograph a graphic card. The instructional materials offered a description of the weather and 3D interactive objects (Figure 7(a)), and the students were able to manipulate the 3D objects and observe variations (Figure 7(b)) through the characteristics of the tablet PC (such as touch, drag, or rotate).

The students were provided with a quiz to reinforce their memory of the learning content when they finished the learning activity in each area. Each quiz for each student had either two or three questions that were randomly selected from the instructional resources. Figure 8 shows an example of a quiz, which was either multiple choice or multiple response. If a student did not pass a quiz, the system would offer remedial materials or require the student to re-learn the learning activity in the current area.

## Method

This study aimed to enhance the students' academic achievement in a natural science course and improve their learning motivation when they used the MAR system to carry out the inquiry-based learning activities. This study adopted the unit "Primary and Junior Middle School Natural and Life Science and Technology-Understanding Weather" as the course contents and extended the learning environment of school to home and a museum. The Taipei Astronomical and Science Education Museum-Earth Exhibition Area was chosen for the museum learning environment. The participants needed to manipulate a tablet PC to take part in the inquiry-based learning activities based on the natural science course. To demonstrate the last two research purposes, this experiment adopted a quasi-experimental control design. The period of the experiment was from May 2012 to June 2012.

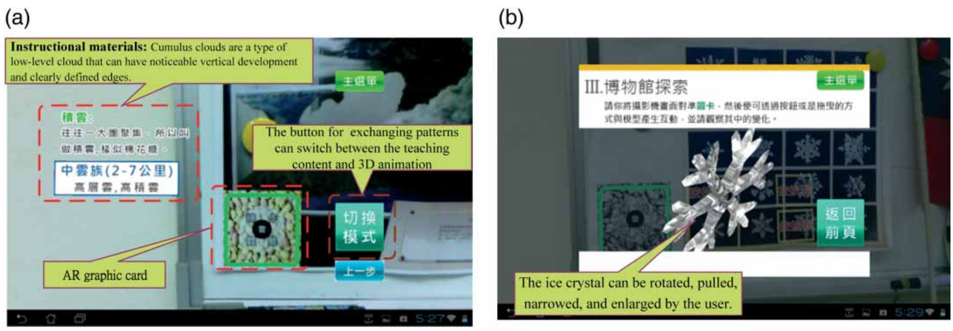


Figure 7. (a) Teaching content for cloud and (b) the snow crystals.

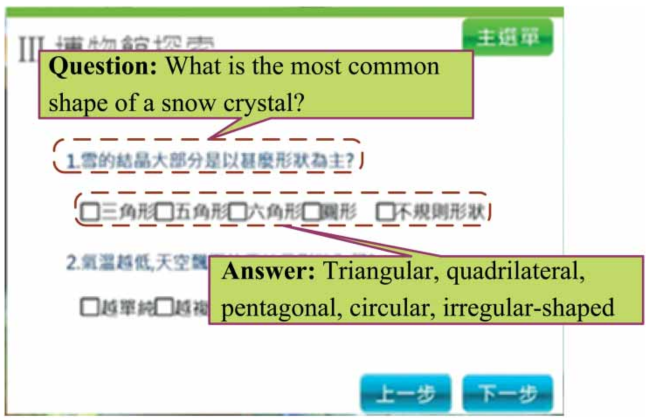


Figure 8. The quiz for a learning activity in one area.

### *Participants*

The participants in this experiment were 64 sixth-grade students (12–13 years old) from 4 classes in Taipei City enrolled in a general studies course entitled “Natural and Life Science and Technology”. Two of these classes comprised the experimental group (EG), which contained 31 students who used the MAR system to study weather factors in different learning environments. The other two classes comprised the control group (CG), which contained 33 students who used the multimedia teaching resources installed on a tablet PC in different learning environments.

These two kinds of teaching tools (the MAR system and the multimedia teaching resources) were the same in content, but there were differences in the content presentation between the MAR system and the multimedia teaching resources. The MAR system had 2D and 3D interactive objects and manipulative aids, while the multimedia teaching resources only had 2D interactive materials.

### *Multimedia teaching resources*

The multimedia teaching resources, with its multimedia contents, guided students to absorb related knowledge of course unit and to complete learning activities’ task. The course unit was divided into five themes: global distribution of climates, the formation of wind, cloud

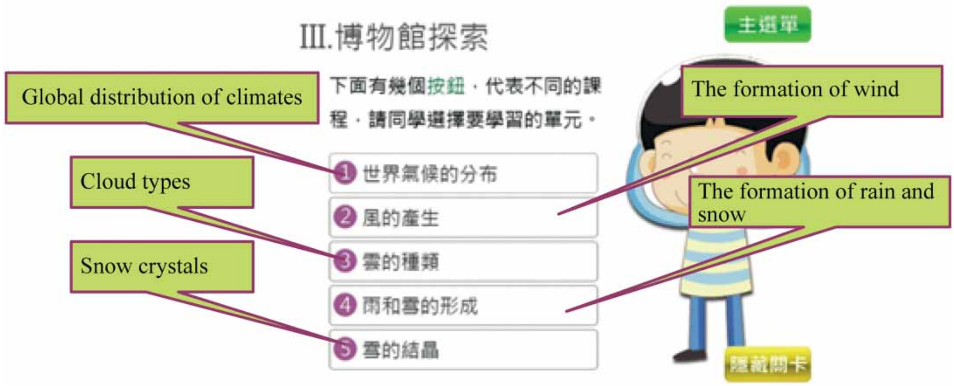


Figure 9. The teaching outline for understanding weather.

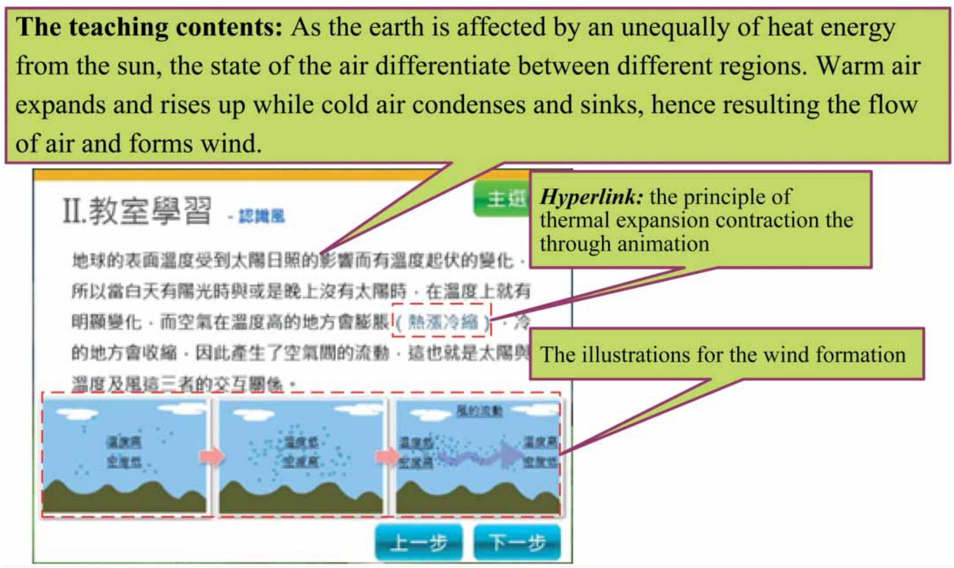


Figure 10. The teaching contents of multimedia teaching resources.

types, the formation of rain and snow, and snow crystals (Figure 9). The resources presented weather factors and weather phenomena with e-books, illustrations, and animation to teach students the concept of weather, such as for the wind formation (shown in Figure 10).

### *Experimental procedure*

Figure 11 shows the experimental procedure. In the first and second week, all the participants (i.e. the CG and the EG) spent 120 minutes on educational training in the operation of the tablet PC before the pre-test of the natural science unit "Understanding Weather". The following week, they took an academic achievement test on the unit to establish their pre-test scores; the test was conducted at the beginning of the course and lasted 20 minutes.

From the beginning of the fourth week until the sixth week, both groups were invited to engage in the inquiry-based learning activities, which took place in three learning

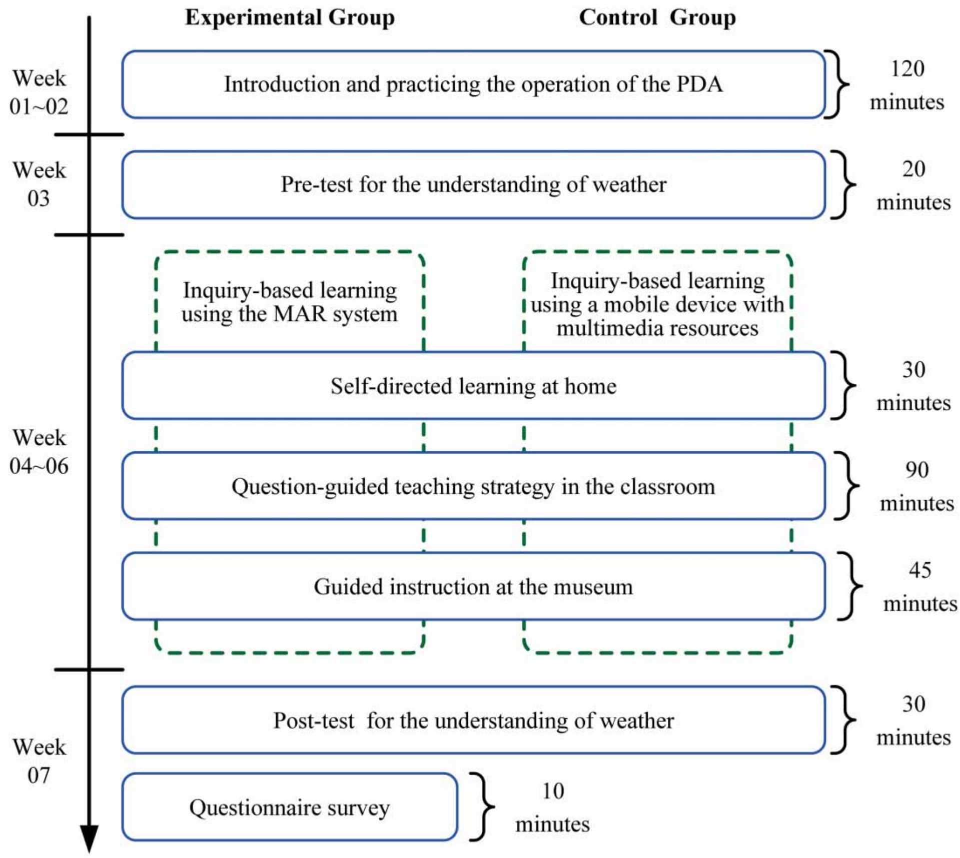


Figure 11. Experimental procedure.

environments, and investigate the "Understanding Weather" unit using different learning systems, respectively. The details of the learning activities in each environment are described in the following sections:

*Home environment*: All the participants (i.e. the EG and the CG) enrolled in the natural science course learned about weather factors in class. After class, the two groups were allowed to explore and complete the worksheets associated with the weather factors using a tablet PC with different learning systems installed and discussing with his/her family circle. This worksheet was designed to be completed in about 30 minutes.

*School environment*: All the participants were involved in the classroom course, where the teacher spent 45 minutes lecturing on weather variations; afterwards, the participants investigated and observed the weather variations by employing either the MAR system (EG) or multimedia content (CG), and then they completed a worksheet on weather variations.

*Museum environment*: Integrating multimedia materials into the museum exhibitions allowed the student to observe realistic weather phenomena, such as snow crystals, to find out what factors caused changes in the weather and to experience interactively the real environment and the virtual world. Moreover, students shared and discussed the experiences they observed with other peers. After the learning activity was completed, all the participants took a post-test to measure their academic achievement in the unit "Understanding Weather", which took about 30 minutes to complete.

This study designed the learning activities in each learning environment based on the inquiry-based learning theory proposed by Bell, Urhahne, Schanze, and Ploetzner (2009), including creating questions, obtaining empirical evidence to answer the questions, explaining the evidence collected, connecting the explanation to the knowledge obtained from the investigative process, and creating an argument and justification for the explanation. The learning process of inquiry-based learning in the two groups is described as follows:

(1) *Creating questions*: Given that the students were just beginning to learn the unit "Understanding Weather", they did not consider the questions meaningful. There were two worksheet designed by two Nature and Science Technology teachers. The questions on the two worksheets referred to a specific learning subject or learning environment, which kindled the students' learning motivation and stimulated them to investigate what factors cause weather.
(2) *Obtaining empirical evidence to answer the questions*: Because many weather phenomena could not be observed in the actual environment during the experimental period, there were three learning modules designed and developed to assist with the experimental activities. Students engaged in the experimental activities could investigate and observe the weather factors and acquire knowledge about weather variations using the MAR system or multimedia materials.
(3) *Explaining the evidence collected and connecting the explanation to the knowledge obtained from the investigative process*: During the learning activities in the three environments, the students could generalize, analyze, and explain the empirical evidence of weather factors that were obtained by repeatedly using the system. Moreover, after completing a learning activity, the students took a quiz and filled out a worksheet associated with the learning activity.
(4) *Creating an argument and justification for the explanation*: After finishing a learning activity in each environment, the students were provide with different formative assessments (quizzes) about the learning activity, allowing them to clarify the contents they learned and to reflect the knowledge gained in the learning activity.

### *Research tools*

There were three research tools employed in this study in addition to the MAR system and multimedia teaching resources: academic achievement tests, worksheets, and a System Satisfaction Questionnaire.

*Achievement tests (pre-test and post-test)*: To demonstrate the influence of different learning systems on academic achievement in the unit "Understanding Weather", there were two tests (i.e. a pre-test and a post-test) designed by two teachers to collect and evaluate the students' academic achievement. The pre-test was used to obtain the students' prior knowledge and understanding of climatology. The maximum score for the pre-test was 72 points. The test consisted of 24 multiple-choice items, which were worth three points each. The maximum score for the post-test was 100 points. The test consisted of 24 multiple-choice items, which were worth three points each, and seven gap-filling items, which were worth four points each.

*Worksheets*: There were two worksheets presented and their rating scales were designed by two professional teachers. One worksheet was associated with weather factors and the other worksheet was associated with weather variations. This study used different evaluating scales to measure the quantity of the students' work, as shown in Table 1.

Table 1. The performance indicators for the rating scales.

| Rating scales | Performance indicators | Description |
|---|---|---|
| Rating for weather factors (Total score: 100) | Obtaining empirical evidence (30%)<br>Explaining the evidence (30%)<br>Creating argument and justification (40%) | To evaluate the score of the worksheets, the two teachers checked the students' worksheets for their completeness on obtaining empirical evidence and explaining the evidence, and their correctness and soundness on creating an argument and its justification |
| Rating for weather variations (Total score: 100) | Obtaining empirical evidence (30%)<br>Explaining the evidence (30%)<br>Creating argument and justification (40%) | |

*System Satisfaction Questionnaire*: Using a mobile learning system, such as the MAR system, to support the learning of natural science is an innovative learning/teaching approach; however, we do not know whether the students like this method of learning. The purpose of the questionnaire was to measure the EG's satisfaction with using the MAR system in different learning environments. The questionnaire adopted a 5-point Likert scale (from "1" being "strongly disagree" to "5" being "strongly agree"), and the questions were divided into three dimensions, which included self-directed learning at home, classroom-guided learning, and museum tour learning, respectively.

## Results

Table 2 shows that the mean (M) and standard deviation (SD) for both groups indicate that there were no significant differences in the prior knowledge of understanding weather ($t = .337$, $p = 737$, Cohen's $d = .084$).

### *The effects of learning tools on the students' academic achievement*

We adopted analysis of covariance (ANCOVA) to analyze the post-test, in which the learning tools (the MAR system and the multimedia materials) were the between-groups factor and the pre-test scores were treated as a covariate to exclude the difference in prior knowledge between the EG and the CG.

A test for homogeneity of variance was conducted, which showed no significant effect ($F_{1,\,60} = .170$, $p = .682$); that is, the data met the requirement for homogeneity of variance. Table 3 shows that the pre-test score was the covariate ($F_{1,\,61} = 54.06$, $p = .000$, $\eta^2 = .47$); the main effect of the learning tools was significantly different ($F_{1,\,61} = 18.3$, $p = .000$) in the post-test score between the EG and the CG, and the effect size ($\eta^2$) was .232.

Table 2. The M and SD for both groups.

| | Pre-test | | Post-test | |
|---|---|---|---|---|
| Group | *M* | SD | *M* | SD |
| EG | 56.13 | 6.24 | 85.77 | 6.328 |
| CG | 55.61 | 6.14 | 80.61 | 5.884 |

Table 3. ANCOVA results in the post-test score for the EG and the CG.

| Group | Number | Adj-*M* (Adjust-Means) | *F*-value (*p*-value) | $R^2$ (Adj-$R^2$) | $\eta^2$ |
|---|---|---|---|---|---|
| EG | 31 | 85.59 | 18.43*** (0.000) | .553 (.538) | .232 |
| CG | 33 | 80.78 | | | |

***$p < 0.001$.

### *The effects of learning tools on the students' inquiry-based learning*

This study analyzed the differences in the scores from the worksheets between the EG and the CG using ANCOVA to eliminate the influence of prior knowledge of understanding weather. In the worksheet for weather factors, before ANCOVA, a test for homogeneity of variance was conducted, with the result revealing an insignificant effect ($F_{1,\ 60} = .005$, $p = .946$); that is, the data met the requirement for homogeneity of variance. Based on the premise that the pre-test was the covariate ($F_{1,\ 61} = 9.64$, $p = .003$, $\eta^2 = .136$), the teaching strategies showed an insignificant difference ($F_{1,\ 61} = 2.02$, $p = .161$, adj-$R^2 = .138$, $\eta^2 = .032$) in the scores from the worksheets between the EG (adj-$M = 88.02$) and the CG (adj-$M = 86.52$). The statistical results of the worksheet for weather variations showed that the interaction of the pre-test and the learning strategies was not significant ($F_{1,\ 60} = .881$, $p = .352$), meaning the data met the requirement for homogeneity of variance. The pre-test was the covariate ($F_{1,\ 61} = 16.81$, $p = .000$, $\eta^2 = .212$); the teaching strategies showed a significant difference in the scores from the worksheets ($F_{1,\ 61} = 32.35$, $p = .000$, adj-$R^2 = .439$, $\eta^2 = .347$), as the scores of the EG (adj-$M = 90.91$) were higher in creativity compared to the scores of the CG (adj-$M = 85.12$).

Table 4. The EG's satisfaction toward using the MAR system.

| Items | *M* | SD |
|---|---|---|
| 1. The learning method for combining the weather factors attracted my interest in the unit "Understanding Weather" | 3.81 | .895 |
| 2. The learning method for combining the weather factors helped me to learn the content | 3.71 | .849 |
| 3. The learning method for combining the weather factors cultivated my thinking skills | 3.94 | .739 |
| 4. A detailed illustration is usefulness when completing each combining task | 3.97 | .897 |
| 5. The MAR system and the combination of weather factors were easy to use | 3.48 | 1.132 |
| 6. The learning method for manipulating the weather controller attracted my interest in the unit "Understanding Weather" | 3.74 | .716 |
| 7. The learning method for manipulating the weather controller helped me to learn the content | 3.74 | .716 |
| 8. The learning method for manipulating the weather controller cultivated my thinking skills | 3.81 | .737 |
| 9. A detailed illustration is usefulness when completing each manipulating task | 3.94 | .878 |
| 10. The MAR system and the manipulative weather controller were easy to use | 3.58 | 1.002 |
| 11. Integrating the 3D interactive material into the museum tasks attracted my learning interest | 3.81 | .644 |
| 12. Integrating the 3D interactive material into the museum tasks helped me to learn more effectively | 3.74 | .670 |
| 13. Integrating the 3D interactive material into the museum tasks cultivated my thinking skills | 3.68 | .737 |
| 14. A detailed illustration is usefulness when completing each museum task | 3.81 | .642 |
| 15. Integrating the 3D interactive materials was easy to perform | 3.58 | .943 |

### *The satisfaction toward using the MAR system*

Table 4 shows the satisfaction levels of the students in the EG toward the use of the MAR system. As revealed in the learners' responses to Item 5, the MAR system was not easy to use at home. However, quite interestingly, a majority of the students expressed that the MAR system helped them to understand weather factors and weather variations; moreover, they had a strong interest in using the MAR system to learn natural science.

## Discussion

Mobile devices such as smartphones and tablet PCs provide students with a portable learning platform to participate in cross-environment learning activities (Lally et al., 2012). Engaging students in different learning environments can help them to acquire diverse knowledge more effectively. This is because knowledge is often acquired in real-life environments (authentic context) of social-cognition and culture through problem solving and social practice (Billett, 1996; Brown, Colllns, & Duguld, 1989; Schell & Black, 1997; Young, 1993). Therefore, many researchers have found that mobile learning can enhance students' academic achievement and learning motivation (Chen, 2011; Di Serio, Ibáñez, & Kloos, 2013; Hwang et al., 2011), to mention just a few areas. However, the following questions remain unanswered: What kind of teaching/learning materials installed on mobile devices can lead to a better effect on academic achievement? What kind of manipulative tools can improve the interactivity and usefulness of AR? In this study, we found that integrating a manipulative AR system (including 3D interactive models and manipulative aids) into inquiry-based field study made a greater positive impact on the students' academic achievement and motivation compared to multimedia teaching resources installed on a tablet PC. Additionally, according to the results, we found two interesting findings related to the use of AR, which will be discussed in detail in the following sections.

### *The MAR system: effective learning materials relative to multimedia teaching resources*

As shown in Table 3, there was a significant difference in academic achievement between the EG using the MAR system and the CG using the multimedia teaching resources, in that the EG students achieved better comprehension and recollection when they were involved in an interactive environment they were able to control and manipulate. There are two reasonable explanations for such a result. First, a coexistent resource of virtual objects and real environments provided students with firsthand experience to investigate unknown phenomena that are not easily observed in real environments (Cheng & Tsai, 2012; Irawati et al., 2008; Klopfer & Squire, 2008). Ha, Lee, and Woo (2011) also indicated that AR could facilitate the students' experiences in multisensory feedback and interactivity with computerized vision-based manual input methods. Second, the students' concentration level was significantly related to the learning process of AR, which fueled the mental operations involved in knowledge acquisition when interacting with 2D and 3D learning objects (a similar result was found by Allen, 2004; Di Serio et al., 2013; Iwata et al., 2011; Sumadio & Rambli, 2010). Therefore, integrating manipulative aids into AR technology provided students with two attractive characteristics: interactivity, which allowed the students to interact with 2D or 3D virtual objects integrated with a real-world environment; and usefulness, which offered an inquiry-based learning task and knowledge about weather factors. These two characteristics drew the students' attention and thus increased their academic achievement and learning motivation.

### *Manipulative aids: an effective learning tool for interactivity and usefulness of AR*

Manipulative aids act as a catalyst to encourage students' learning initiative and offer a user-friendly and highly interactive interface to bridge the gap between AR teaching materials and the inquiry-based learning process. Integrating manipulative aids, the AR teaching materials are effective in attracting and holding the attention of students and fostering their thinking skills. This is because learning is a process in which knowledge is acquired through a transformative experience, such as learning by doing (Dewey, 1938; Kaagan, 1999) rather than just listening or observing. Chang, Chen, and Hsu (2011) demonstrated that integrating a hands-on learning activity into an outdoor environment can improve students' learning motivation and their degree of participation, as well as enhance their academic achievement. This study also achieved similar findings. The results of inquiry-based learning indicate that the intervention of manipulative aids can assist students in finding better empirical evidence, fully interpreting it, and producing convincing arguments and their justification compared to using multimedia teaching resources; specifically, manipulative aids, such as the weather controller, provide a high level of interactivity and entertainment.

## Conclusion

This study designed and implemented a MAR system to teach the unit "Understanding Weather" in a natural science course. There were three sub-modules with different learning contents in the MAR system developed to bridge formal learning, non-formal, and informal learning to support different environments (i.e. at home, in school, and at a museum). The system provided students with hands-on' experimentation and minds-on reflection to investigate the factors that cause weather variations.

### *Contribution*

The major contribution of this study was to improve the interactivity and usefulness of AR by replacing the fixed AR graphic card with manipulative tools, and to demonstrate that employing manipulative aids as an accelerator strengthens interactivity among students, the AR teaching system, and the real environment. The manipulative aids, with AR teaching materials (i.e. virtual objects and real exhibitions), engaged students in inquiry-based field study, where they learned about weather factors and completed learning tasks related to what they learned, such as worksheets and quizzes.

This study examined the differences between the students' academic achievement in a natural science course using the MAR system and multimedia teaching resources. Sixty-four sixth-grade students were invited to participate in this experiment and were divided into an EG and a CG. The results revealed that the MAR system installed on the tablet PC made a greater positive impact on the students' academic achievement and motivation compared to the multimedia teaching resources installed on the tablet PC.

In addition, this study addressed two interesting findings related to the effectives of the AR system and manipulative aids. First, the MAR system was a more effective learning companion compared to multimedia teaching resources. To be precise, the characteristics of the MAR system, such as the simultaneity of virtual and real objects, high interactivity, and hands-on experience, made a greater positive impact on the students' academic achievement and motivation. Second, unlike multimedia teaching resources that only allow students to listen or observe, manipulative aids decrease the distance between students and the AR teaching materials and increase the interactivity and usefulness of AR technology.

### *Suggestions and future work*

We originally focused on the differences between integrating manipulative aids into an AR interactive environment and multimedia teaching resources. However, we observed that most of the students in the EG achieved better participation levels when they interacted with the MAR system compared to the students in the CG who used multimedia teaching resources during the period of our research. Additionally, there are two meaningful suggestions associated with designing and developing the AR educational system for future researchers and designers**:**

#### *Make it easy to use*

Chang et al. (2011) indicated that the use of an intervening marker or manipulative aids for the AR system did not easily engage students in inquiry-based learning, and this argument was found in this study. We suggest that manipulative aids and the AR system should probably focus on simplicity and ease of providing education and training experiences so that students can acquire knowledge and skills with 3D simulations generated by mobile devices and other aids.

#### *Include manipulative aids*

According to our results found in inquiry-based learning, there was a significant difference in the worksheets for weather variations between the EG and the CG, whereas for worksheets for weather factors there was no significant difference. We suggest three design principles for manipulative aids: (1) interactivity, which offers students more opportunities to interact with 2D and 3D objects and the real environment; (2) entertainment, which allows students to control their own learning process (i.e. like playing games); and (3) usefulness, which offers meaningful tools associated with a learning topic. For example, the weather controller that was designed and developed by this study aligned with the topic of weather variations and encouraged students to investigate unknown knowledge more actively during the learning process.

Although the proposed MAR system is useful for improve students' academic achievement and learning motivation by integrating manipulative interactive tools with a real-world environment, several issues need to further improvement. First, in spite of the influence of the multimedia eliminated, the results do not know whether improvement in academic achievement was due to the use of AR systems or due to the manipulative interactive tool. We suggested that future study can record the overall activity that occurred during the students' manipulative process (such as Gazing, interacting with AR, or replying to questions) in order to analyze the differences in the learning behaviors between the fixed AR system and the MAR system, and find out that a causal relationship exist between their learning behaviors and academic achievement. Second, the MAR system offered students additional scaffolding and support which would help them to search for possible solutions to their task and to interpret clues provided by the technological devices and embedded in the educational fields. However, the following question remains unanswered: What kind of educational fields in which MAR system was applied could lead to a better effect on learning performance? It would be interesting to include a comparative study between the different levels of formal, non-formal, and informal.

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## Note

1. Formal learning consists of learning that occurs within a planned and structured context (such as formal education, in-company training, etc.), whereas non-formal learning consists of learning embedded in planned activities in a meaningful context (such as museums, zoos, or planetariums) that may be fascinate with the student's learning motivation; informal learning is defined as learning resulting from daily life activities related to work, family, or leisure (Coombs & Ahmed, 1974; Eshach, 2007; Mocker & Spear, 1982).

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