Teaching the Various Features of Scientific Observation

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I. Introduction

When two electric bulbs are connected to a battery in series, some students predict that the first bulb connected to the plus polarity of the battery will be brighter because electric current or energy will be decreased after passing the first bulb. In this case, Park & Kim (2004) found that, when observing the brightness of two electric bulbs directly, about 50% of students who predicted that the first bulb would be brighter described that the firs bulb was brighter even though the brightness of two bulbs were actually equal. This is a typical instance showing the impact of an observer's knowledge or experience on scientific observation.

Inversely, if students have no relevant knowledge related to observation, they sometimes do not recognize whether their observation is meaningful or not. For instance, when students draw what they observed about onion cell through a microscope, a student may draw a large circle three-dimensionally. In fact, he/she draws the small air bubble formed between the slide glass and the cover glass rather than the cell of layer of onion (000). Therefore, if he/she had relevant basic knowledge about the plant cell, they could recognize that his/her observation was something wrong.

These two simple instances mean that that observation alone cannot lead to falsification, even after the conflicting observation evidence is presented (Lakatos, 1994, p. 35; Park et al., 2001) because of the observer's prior idea, and we also know that some scientific observation can be possible for only observer who has relevant knowledge.

Besides the above aspects of scientific observation, many philosophers of science, science educators, and psychologists have mentioned various features of scientific observation. For instance, scientific observation can be impacted by observer's attention (Brewer & Lambert, 2000) or influenced by choosing where or what to direct the visual process (Pylyshyn, 2006). And Morgan (2011) noted that "scientific observation involves not just the processes of observing, but ones of recording and reporting these observations." (p. 303). That is, scientific observation should be described in the form of a statement using scientific language (Chalmers, 1986, pp. 28-32). And scientific observation is also closely related to other inquiry skills. For instance, observation involves activities of discriminating or categorizing sensory input (Heath, 1980), or inferring and interpreting also (Gale & Walter, 1973). Hodson (1996) additionally noted that, (1) observations are unreliable and fallible because it depends on the inadequate human sense, (2) observation using instrument depends on the theory of instrumentation, (3) concepts and theories cannot be derived direct observations, (4) competing theories can cause different observation for the same phenomena, and so on.

The reason that there are many features in scientific observation is because scientific observation is not a process to be carried out in isolation, but actually a very complex process (Haslem & Gunstone, 1997) conducted under the connection with scientific concepts or observer's background knowledge and experience, with other inquiry skills and with physiological features of human senses. However, many students think that observation is a simple process in scientific inquiry, because it can be done just by seeing something in detail (Eberbach & Crowley, 2009). In this case, while students observed minute details of natural phenomena or scientific events, they often fail to make scientifically meaningful observation.

Therefore, the basic goal of this study is to summarize and categorize various features of scientific observation emphasized by different science educators, philosopher of science, or psychologists, and to discuss the educational implication suggested by each feature of scientific observation.

The features of scientific observation belongs to the nature of science which has been stressed in science curriculum (NRC, 1996; NRC, 2000; NSTA, 2000; AAAS, 1994; PBC, 1996; Donnelly, 2001), for achieving scientific literacy (Matthews, 1004; Lederman, 1999; Bell and Lederman, 2003, Osborne, et al., 2003), for helping conceptual understanding (Windschitl and Andre, 1998; Tsai, 2001), and for improving the skill of scientific inquiry (Vhurumuku, et al., 2006; Sandoval and Reiser, 2004; Toth, et al., 2002; Bell and Linn, 2000).

However, many science educators have pointed out that students' scientific inquiry activities in school do not reflect the NOS (Driver et al. 1996), and most schools and almost all science textbooks did not take an epistemologically sound standpoint (Hodson, 1998; Chinn and Malhotra, 2002). Therefore, many science educators have tried to design more authentic scientific inquiry based on the NOS.

However, when we summarize well-known six studies to teach the NOS (Lederman & Abd-El-Khalickm 1998; Bianchini & Coburn, 2000; Lederman et al., 2002; Ping-Kee Tao, 2003; Bartholomew, Osborne, & Ratcliffe, 2004; Sandoval, 2005; Akerson, et al., 2006), we found that only two studies (Lederman & Abd-El-Khalickm 1998; Akerson, et al., 2006) included the feature of the scientific observation (that is, 'Observation differs from inference', 'Observation is theory laden', and 'Inferences are explanations for observation') as elements of the NOS to be taught. Others stress the nature of scientific knowledge (e.g., Scientific knowledge is tentative), scientific inquiry process (e.g., There are multiple methods of inquiry, and those methods require empirical evidence), and other features of the NOS (e.g., Scientists need to be creative and imaginative).

Therefore, some educators have criticized that the importance of scientific observation have been underestimated in science education (Chinn & Malhotra, 2002a; Metz, 2000; Norris, 1985; Sminth & Reiser, 2005) Therefore, after summarizing and categorizing various features of scientific observation, we tried to help students to understand these various features of scientific observation. In fact, the features of scientific observation are related to the philosophy of science and psychology, which are not easy to be understood by high school students. However, we believe that teaching the features of scientific observation is sufficiently meaningful for understanding the NOS and for conducting scientific inquiry in a more authentic way. Therefore, we developed learning materials and applied it to senior high school students, and investigated the effectiveness of it. In the above-mentioned background, the detailed purposes of this study are to;

- extract and summarize various features of scientific observation from the literature review,
- develop learning materials for helping students to understand various features of scientific observation,
- apply learning materials to students, and investigate the effectiveness of the application.

Extraction and classification of statements describing the features of scientific observation

Many science educators, philosopher of science, and psychologists have described various features of scientific observation. Therefore, at first, we extracted and summarized various descriptions about the scientific observation from the literature review. And we collected similar descriptions about scientific observation, and represent a statement describing a common feature of these similar descriptions. Following is an example:

The statement: "Some observation is often possible to only person who has specific scientific knowledge"

And we classified the various statements into several categories. As a result, we could classify 10 statements as shown in Table 1. Details of each statement will be described in result section.

[Table 1] Statements describing the future of scientific observation

1. Some observation is often possible to only person who has specific scientific knowledge.
2. The observer often observes selectively with a specific purpose or expectation.
3. Observation can be varied by the change of surrounding context or condition.
4. When using observatory instruments for more precise observation, observational result can differ from with the reality.
5. Observation is not the same with the image formed on eye retina. Observation is something above the optical image on the retina.
6. Observation includes interpretations intrinsically.

7.	Some observations are constructed or 'mixed and matched' with limited observatory information.
8.	Observation may not be objective because different observation can always be possible.
9.	None of the observations can be complete or perfect.
10.	The observation should be described as a linguistic statement.

Statements describing the features of scientific observation

Ten statements describing the nature of scientific observation in Table 1 cannot be a complete taxonomy for scientific observation. Therefore, we need to have continued concern on revising and supplementing the list for more comprehensive understanding about the nature of scientific observation. However, the statements in Table 1 can be a useful starting point for helping teachers to teach the nature of scientific observation in a more concrete way. The followings are detailed description for each statement.

Statement 1. Some observation is often possible to only person who has specific scientific knowledge.

Since the late 1950s, philosopher of scientists emphasized that scientific observation is theory-laden (e.g., Charmlers, 1986; Hanson, 1961). Hanson (1961, p. 19) noted that "Observation of *x* is shaped by prior knowledge of *x*", and therefore, "learning does not go from observation to theory, but always involves both elements." (Feyerabend, 1976, p. 168).

The 'Statement 1' is especially about the case when theory takes a decisive role in whether observer can observe something actually or not. For instance, when novice sees the X-ray photograph, he/she cannot observe any symptom of pneumonia even after doctor indicates it on the photograph. Likewise, only professional physicists can observe the elementary particles, such as positron, in the photograph of cloud chamber (Ladyman, 2002, p. 112). Watson & Crick, who discovered the DNA structure, realized that DNA had a regular structure from the photograph DNA using X-ray in the spring of 1951. Therefore, they started to study the X-ray diffraction patterns, as a result, this works could lead them to interpret and understand the DNA X-ray photograph more in detail (Weisberg, 2006, pp. 16~19). About this process, Weisberg (2006, p. 19) noted that "… seeing a helical pattern in the X-ray … is not the same as seeing a smile on the face of your friend. … One must understand X-ray crystallography in order to see a helical pattern in an X-ray photograph."

The 'Statement 1' gives an important implication for teaching observational skills in students' scientific inquiry, because some students may not learn at all if he/she does not have the relevant knowledge before observing something (Brown, 1977, p. 87). For example, Eberbach & Crowley (2009, p. 40) noted that "(when students observe the birds) Lacking this specialized knowledge (about the birds) and practice, students were unable to make scientifically meaningful observations."

Statement 2. The observer often observes selectively with a specific purpose or expectation.

When we focus on specific aspects of the observed object, we often miss other ignored aspects of it. For example, when students try to measure the electric current, they focus on the number indicated by the needle of ampere meter, but ignore the brand or trademark of the ampere meter. In the area of neuroscience, Rees, et al. (1999) tested, when observer does not give attention to the words or figures, whether he/she fails in perceiving it (that is, he/she does not observe even though he/she 'sees' it) or he/she rapidly forget it after observing it. Using FMRI technique, they concluded that people often do not observe anything even when they 'look at' directly if they don't give attention to it.

This is another feature of theory-ladenness of observation, because 'choosing where or to want to direct the visual process' is influenced by the cognitive system (Pylyshyn, 2006). Brewer & Lambert (2000) said that "Another important way that theories can impact the scientific process is through attention" (p. S180). The reason that the observation is selective is because observing all of things without ignoring anything requires a great cognitive burden (Gerrig & Zimbardo, 2008, p. 123). In this case, determination about which aspects should be focused on depends on the purpose of observation as well as impressive aspects of an object or event to be observed (Bunge, 1998, p. 182). Therefore, the teacher needs to present the purpose of observational activities to students in more concretely (Driver, 1983, pp. 12, 21-23). That is, according to the purpose of observation, such as finding specific fact, testing the suggested hypotheses, or comparing it with the prediction, teacher needs to encourage students to focus specific aspects of an object or event.

However, this encouragement is not appropriate for improving creativity. For the creativity, students are required to observe as many (for fluency) and various (for flexibility) as possible, and to find observations which others miss, ignore or fail to percept (for originality) (Hu & Adey, 2002; Cropley, 2003, p. 102). For example, Rontgen’s observation was not purposeful but unexpected one. In fact, many students have been trained to find out what was required by the objective of the inquiry activity or teacher wanted. As a result, when observing something, many students rapidly finish their observational activity when they realize that they find out what inquiry program wants. Therefore, for creativity, teachers need to have opposite position to the ‘Statement 2’.

Statement 3. Observation can be varied by the change of surrounding context or condition.

‘Brightness constancy’ is a typical instance of observation affected by surrounding context (Adelson, 1993). In Fig. 1, you will perceive that cell a_1 is darker than cell a_2. However, if surrounding background is covered, then you can observe that the brightness of two cells are the same. That is, the perception of different brightness in Fig. 1 is because of the different surrounding brightness. Fig. 2 is another example. The figure in the center in Fig.2 looks ‘B’ if you read it from left to right, but it looks ‘13’ if you read it from top to down (Atkinson et al., 1983, p. 146). Therefore, Ramachandran & Blakeslee (1998, p. 82) mentioned that “… perception is always relative - never absolute - always dependent on the surrounding context.”

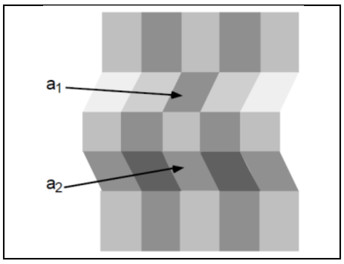

Fig. 1 Same brightness of a_1 cell and a_2 cell (Adelson, 1993)

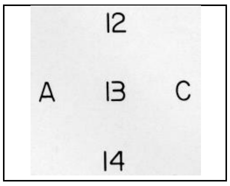

Fig. 2 The figure in the center looks ‘B’ or ‘13’ (Atkinson et al., 1983, p. 146)

In a scientific context, observation is always conducted under certain conditions. For example, the boiling temperature of water varies under the atmosphere or altitude of observing the place. Therefore, recoding observation should be accompanied with describing surrounding conditions, such as temperature, air pressure, brightness, altitude, and so on. The teacher should help students to recognize this point when observing something.

Statement 4. When using observatory instruments for more precise observation, observational result can differ from with the reality.

When using instruments for observation, there are various functions of the instruments (Heidelberger, 2003). At first, scientific instrument can be used to produce phenomena which cannot be directly experienced by normal human senses (e.g., X-ray). And it can expand or improve human perception (e.g., microscope) or make a very uncommon event easy to be happening (e.g., high-voltage instrument makes lightning easily in wanted space and time). In other cases, the instrument makes us observe the effect rather than the cause which can be perceived directly (e.g., using sensors, we can obtain electric voltage produced by the influence of the cause, such as pressure or temperature), or theoretical entity such as an electron (by electroscope) or positron (by cloud chamber).

In the use of instruments, the important point is that theories embedded on the instruments and technical processes from the raw phenomena to the finalized observation (Gilles, 1993, p. 146). Therefore, passing through the instrument, the information going out from the equipment can be different from the information coming into the instrument from the object or event, because the instrument can give effect on the information from the outer world. For example, when observing the object using the magnifying lens, we can observe the color on the edge of the observed object, however, this color does not exist in real object but generated by chromatic aberration of the lens. And also the observed electric current using the ampere meter is not the same with the actual electric current without the ampere meter, because the internal resistance of the ampere meter has already changed the original electric current.

However, students usually think that the use of instruments can raise the accuracy. Therefore, teachers need to help students realize that instrument can give impact on the real world; as a result, the observed result may be different from the actual world.

Statement 5. Observation is not the same with the image formed on eye retina. Observation is something above the optical image on the retina.

When we observe something, the visual image in human retina is upside down and also 2-dimensional image, however, we observe the phenomena stood up straight 3-dimensionally. And if the red color of light and the green color of light come into our eyes simultaneously, then we recognize it as a yellow color of light and we cannot discriminate this mixed yellow with pure yellow having a single wavelength. Therefore, Hanson (1958, pp. 23-24) noted that “there is more to seeing than meets the eyeball” (Hanson, 1961, p. 7). Chalmers (1986, p. 24) also noted that (visual) experience cannot be determined solely by ‘the images on the retinas of an observer’.

Park & Kim (2003) classified the process of observation into two processes: physical process and cognitive process (Fig. 3). According to them, even though optical information formed on retina during the physical process, final observation may be different through the cognitive action.

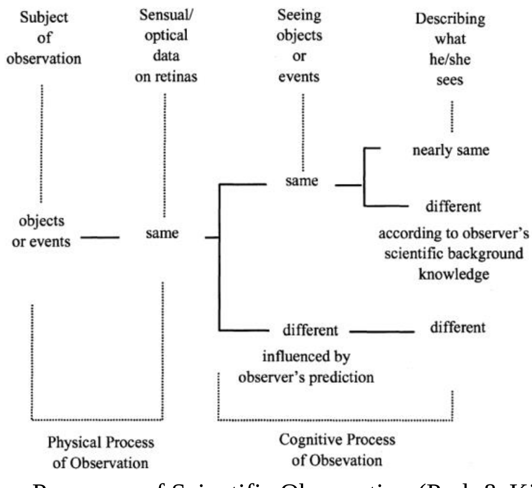

Fig. 3 Two Processes of Scientific Observation (Park & Kim, 2003)

Many science educators have emphasized the relationship between science and other disciplines or everyday life (e.g., Campbell et al., 2000; Park & Lee, 2004; Bybee 2010). The process of formation of images in the retina is a part of physics and biology, but the perception of it in the human brain is a part of psychology and neurology. Therefore, we expect that the understanding about the process of perception from the optical information formed in the retina to 'what they observe' will be an interesting topic for teaching 'integrated science' or 'everyday science'.

Statement 6. Observation includes interpretations intrinsically.

When scientists observe the cloud chamber, they do not observe only the white lines, but are simultaneously inferring the charges, masses, or kinds, of elementary particles, or often testing theoretical predictions or hypotheses. In modern science, scientists observe the many points, in the screen, obtained from complicated measuring equipment. Here, scientists report their observations as 'solar neutrino is observed', rather than 'points, construct a line' (Pinch, 1985, p. 9).

In this process of observation, scientists often describe their observations differently. In this case, students may think that 'interpretation is different after conducting the same observation' (Chalmers, 1986, p. 27). However, the 'Statement 6' emphasizes that the observations themselves are different rather than the interpretations are different for the same observation. Therefore, in the activity of scientific inquiry, students need to compare their observations, and if the observations are different, they need to the reasons of difference rather than to try to choose the correct one. This means that, when students record their observations, they may be required to explain the reason why they describe like that. For example, when recording observation about the candle, some students describe simply what they observed like, 'flame has various colors such as yellow, red, orange, and blue color', but others can describe like, 'the temperature of lower and outer part of the flame is higher than other parts'. Then, two observations are different and correct. But in the latter case, it is recommended to describe the reason together, such that 'because the flame of shorter wavelength has the higher temperature.'

Statement 7. Some observations are constructed or 'mixed and matched' with limited observatory information.

Even though the information is fragmented or ambiguous like Fig, 4, we can say that 'I observe the dog'. That is, limited number of small perceptual information can be organized in bigger form of observation, where some omitted perceptual information are reconstructed as if they are perceived. As another example, drawing lines on the discrete points imprinted in the graph is also similar process. That is, with only a limited number of discrete points, scientists said that 'This variable is linearly proportional to that variable.' This feature is related to 'gestalt', that is, "… a group of German psychologists became intrigued with how the mind organizes sensations into perceptions. Given a cluster of sensations, the human perceives them into a gestalt, a German word meaning a "form" or a "whole". (Myers, 1993, p. 126).

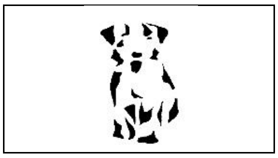

Fig 4. Fragmented Figure (Pylyshyn, 2006, p. 78)

This is the ordinary case in scientific inquiry also. Let's imagine a paleontologist describing what he/she observes the unearthed fossils of bones of dinosaur. His/her observation may be recorded like, 'This huge dinosaur stayed mainly near water to cool down their body temperature', with the limited number of broken bones. Here, the interesting point is that, the ‘Statement 7’ has an opposite characteristic compared to the ‘Statement 2’. In ‘Statement 2’, some visual information is neglected in the observation even though optical information are reached into human retina, however, in ‘Statement 7’, some observations are described even though there is no visual information about it at all. That is, the ‘statement 7’ emphasizes the organizational and constructive process with incomplete visual information in observation.

Statement 8. Observation may not be objective because different observation can always be possible.

As mentioned earlier, scientific observations may always be different by different observers. Here, we emphasize the case when two different observations cannot be reconciled even after two observations are compared directly. For instance, when observing ‘the old woman/young woman picture’ (Boring, 1930; Gregory, 1997, p. 206), some observe only old woman and fail to perceive the young woman, however, reverse phenomena happen to other observers, even they all ‘see’ the same picture. In this case, two observers cannot communicate with each other about their observations. This means that objective observation may not be possible in some situations. Therefore, Brown (1977, p. 87) said that “… different perceivers with different information learn different things from observing a single object”. This is similar with two scientists living in different worlds of paradigm. That is, if the paradigm is changed “after a revolution scientists work in a different world.” (Kuhn, 1970, p. 135)

However, we need to careful not to exaggerate the non-objectivity of scientific observation. Important point, here, is that scientific observations cannot be always completely the same in any cases. In many cases, objective observations are possible, therefore, “(theory-ladenness of observation) is not so sensitive as to make communication, and science, impossible” (Charlmers, 1986, p. 27) or, theories embedded on the observation are often relatively irrelevant to theories which will be tested by observation (Kosso, 1989, p. 246). For example, the observation that “the temperature of the flame of candle differs in and out of the flame” may not be possible for some observers if they do not have relevant knowledge about the relationship between color and temperature. However, the observation that “The flame of a candle has different colors” is possible for almost all observers.

Statement 9. None of the observations can be complete or perfect.

Another interesting thing is that observer sometimes fails the correct observation even after he/she knows what observation should be. Typical examples of this are Muller-Lyre illusion figure (Gregory, 1997, p. 219) and perception of yellow color. In Muller-Lyre figure, observer observes that lengths of two lines are different, even after he/she realized that they have the same length after measuring them using the scale. And if the red color of light is mixed with green color of light, all of us perceive it as yellow color of light. As a result, we cannot discriminate it with real yellow color having only one wavelength. These two examples are interesting because theory does not give any effect on observation (Fodor, 1984). That is, even though observer already knows what the correct observation should be, he/she observes differential with what they know. Therefore, many philosophers of science have stressed that perception or observation cannot be complete or trustful because it is fallible. We already know that prior misconception can lead to incorrect observation (Park & Kim, 2004).

Because of the statement 9, some science teachers worry about that the incompleteness of scientific observation and knowledge can make students think that science is useless to be learned. However, Park & Kim (2008) observed that students who learned the features of the NOS regarding the imperfection of the scientific knowledge felt the freedom through which they could invent or discover something new. Therefore, I believe that understanding the statement 9 has sufficiently educational meaning.

Statement 10. The observation should be described as a linguistic statement.

Moragn (2011, p. 303) noted that “scientific observation involves not just the processes of observing, but ones of recording and reporting these observations.” However, students often think that observation is an activity which is just seeing something, do not think that observation should be recorded as a form of statement. Ford (2005) observed that, when 3rd grade elementary school children observed rock and mineral samples, many of them were enthusiastic about observation but little wrote down their observation as descriptions. Gleason & Schauble (2000) also observed that 9 to 12 children recorded a mere 5% of data what they obtained, and only 1% of the results.

In fact, writing is an important component in scientific inquiry. For instance, in ‘ASE Science Teachers’ handbook’ in England, the communication skill was already stressed as one of process skills with two other skills, that is, thinking skills and practical skills (Miler, 1986, p. 5). However, Garcia-Mila & Andersen (2007) noted that writing in learning science have been little considered in improving scientific reasoning. This means that we need to develop more practical and detailed teaching strategies for guiding student what and how to write what they observe. Regarding this, studies to improving writing skills in scientific inquiry process (e.g., Wellington & Osborne, 2001; Darian, 2003; Keys et al., 1999) can give us solution about this.