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ARTICLE

Lucky Belief in Science Education

Gettier Cases and the Value of Reliable Belief-Forming Processes

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Abstract The conceptualisation of knowledge as justified true belief has been shown to be, at the very least, an incomplete account. One challenge to the justified true belief model arises from the proposition of situations in which a person possesses a belief that is both justified and true which some philosophers intuit should not be classified as knowledge. Though situations of this type have been imagined by a number of writers, they have come to be labelled Gettier cases. Gettier cases arise when a fallible justification happens to lead to a true belief in one context, a case of 'lucky belief'. In this article, it is argued that students studying science may make claims that resemble Gettier cases. In some contexts, a student may make a claim that is both justified and true but which arises from an alternative conception of a scientific concept. A number of instances of lucky belief in topics in science education are considered leading to an examination of the criteria teachers use to assess students' claims in different contexts. The possibility of lucky belief leads to the proposal that, in addition to the acquisition of justified true beliefs, the development of reliable belief-forming processes is a significant goal of science education. The pedagogic value of various kinds of claims is considered and, it is argued, the criteria used to judge claims may be adjusted to suit the context of assessment. It is suggested that teachers should be alert to instances of lucky belief that mask alternative conceptions.

1 Introduction

Amongst the many constructs used to describe learning in science education, knowledge is a widely used term (Taber 2013). For example, researchers refer to students' knowledge structures (Driver and Oldham 1986; Novak 1990; Osborne and Wittrock 1983) and students' and teachers' knowledge of various concepts (Chinn and Brewer 1993; Hogan 2000; Justi and

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Gilbert 2002). The concept of knowledge has been used with a variety of different meanings in the science education literature (Southerland et al. 2001). Whilst some constructivists have argued that knowledge is difficult to distinguish from belief (Cobern 1993, 2000), it is reported that 'many science educators' (Sinatra et al. 2003, p. 511) have defined knowledge as justified true belief (JTB). In general, some form of justification is seen as a necessary component of models of empirical knowledge (Moser 1985) and teaching students the justifications for scientific propositions has become a requirement of some science curricula (Hennessey et al. 2013). Many science teachers might, therefore, reasonably believe that if a student makes a claim that is both justified and true, then successful learning has taken place.

However, many epistemologists believe that a class of thought experiments, developed to critique the JTB model of knowledge and commonly referred to as Gettier cases, describes situations in which a belief that is both justified and true should not be considered as knowledge (Turri 2012b). This article examines a number of similar cases in the context of the science classroom in which a student holds a belief that is both justified and true but which arises from an alternative conception. Such cases are considered to be instances of 'epistemic luck' (Pritchard 2005) because, though the alternative conception may generally lead to false beliefs, it happens, in one context, to produce a true belief. An examination of these cases in the context of science education prompts a discussion of the criteria teachers use to judge learning. The article proposes two approaches to examining evidence of learning that can highlight cases in which lucky belief has occurred.

2 The Justified True Belief Model of Knowledge

In the *Theaetetus* dialogue, Plato reported an argument that knowledge should be defined as a true judgement for which the knower has some account:

> I once heard a man say… that it is true judgement with an account that is knowledge; true judgement without an account falls outside of knowledge. And he said that the things of which there is no account are not knowable (yes, he actually called them that), while those which have an account are knowable. (Plato 1992, p. 80)

According to this account, which has been labelled the justified true belief (JTB) model, a person knows some proposition, p, if (i) p is true; (ii) they believe that p is the case; and (iii) they have good reasons for believing p (Klein 1971). Two misconceptions are associated with the JTB model. Firstly, though the JTB model of knowledge has come to be associated with Plato, it has been suggested that he introduced the construct in order to highlight its flaws (Cellucci 2017): he argued it would be absurd to associate knowledge with true belief supported by some form of justification (Plato 1992). Secondly, whilst it has been claimed that the JTB model of knowledge was taken for granted by the majority of philosophers until the middle of the twentieth century (BonJour 2001; Hetherington 2011), several scholars (Le Morvan 2017; Plantinga 1993) have pointed out that this analysis overstates the orthodoxy of the model and that there are few clear assertions of the JTB account of knowledge in the history of epistemology. Following Plato's critique, several authors have raised objections to the JTB model (see below) and it has been reported that '[m]ost philosophers' (Turri 2012b, p. 247) believe that the JTB account, by itself, is an insufficient account of knowing. The next sections consider some thought experiments that indicate the inadequacy of the JTB model of knowledge.

3 Challenges to the Justified True Belief Model

Though cases that suggest that JTB is not knowledge have been proposed by several authors, including the Indian philosophers Prasastapada in the sixth century and Sri Harsa in the eleventh century (Parikh and Renero 2017), it has become conventional to refer to such situations as Gettier cases after the writer who popularised interest in them in the twentieth century (Turri 2012a). One example, from the Indian tradition, describes the case of a person who observes a dark cloud over some mountains and develops a belief that there is a fire beneath the cloud (Parikh and Renero 2017). However, the dark cloud turns out to have been dust rather than smoke, but, by coincidence, a fire was burning beneath the dust. Both Sri Harsa and Prasastapada argue that the observer does not have knowledge of the fire. In the early twentieth century, Russell (1912) described a number of thought experiments that indicated the inadequacy of the JTB model. He argued that there was an "inevitable vagueness and inexactitude" (Russell 1948, p. 170) associated with the concept of knowledge and illustrated his claim with a thought experiment about a stopped clock:

> "Knowledge" is sometimes defined as "true belief", but this definition is too wide. If you look at a clock which you believe to be going, but which in fact has stopped, and you happen to look at it at a moment when it is right, you will acquire a true belief as to the time of day, but you cannot be correctly said to have knowledge. (Russell 1948, p. 113)

Russell's example includes both the features of Gettier problems introduced below, 'luckiness' (the clock is observed at a moment when it displays the correct time) and 'fallibility of justification' (the clock is not a reliable source of the correct time) (Hetherington 2011, p. 121). However, the thought experiment attracted little attention at the time it was published (Bigelow 2006) and it was not until the second half of the twentieth century that interest in similar cases began to increase.

In 1963, Edmund Gettier published a three-page paper which has had an immense influence on epistemology (Foley 2002) and renewed discussion of the JTB model of knowledge. Gettier (1963) proposed a thought experiment that considered two people, Smith and Jones, who have applied for a job at a company. The president of the company has told Smith that Jones will get the post, and Smith is also aware that Jones has ten coins in his pocket. Smith therefore holds the justified belief that the person who will get the job has ten coins in their pocket. However, it turns out that Smith eventually gets the job and, though he is unaware of it, he also has ten coins in his pocket. Gettier argued that Smith's belief that a person with ten coins in their pocket would get the job is both true and justified, but intuitively seems to fall short of the status of knowledge. Amongst contemporary philosophers (but not, research suggests, other groups of people—see below) there is a widespread agreement that Smith's belief is not knowledge (Turri 2013). Subsequently, other examples of similar situations, have been proposed, for example, 'The sheep in the field' (Chisholm 1966) and 'The fake barns' (Goldman 1976) cases. Though the categorisation of some of these examples as Gettier cases is contentious (Heathcote 2012), two features are believed to be present in Gettier cases:

> (1) *Fallibility.* The justificatory support is *fallible*. It indicates strongly–without proving conclusively–that the belief is true.
> (2) *Luck.* Within each case, the well-but-fallibly justified belief is true. (Hetherington 2011, p. 121, Italics in original)

Gettier cases have been taken to indicate that the JTB model is "…at the very least seriously incomplete and quite possibly even more badly mistaken" (BonJour 2001, p. 40) and epistemologists have yet to reach a consensus on an alternative model of knowledge (Bigelow 2006). A number of different strategies to address the apparent inadequacy of the JTB model of knowledge have been proposed:

- Knowledge should be redefined to require infallible justifications for beliefs.
- A belief should not be considered knowledge if the justification occurs through an accidental occurrence.
- Knowledge may not be justified by a false belief.
- A belief must be caused by appropriate evidence.
- The intuition that Gettier cases do not represent knowledge should be discarded.

(Hetherington 2011, pp. 122–128)

Gettier cases are predicated on the assumption that the JTBs asserted do not represent knowledge. Whilst it is claimed that nearly all published interpretations, with a few exceptions, agree with this intuition, empirical studies of the views of philosophers on the knowledge status of Gettier cases have not been carried out (Turri 2016). Experimental epistemologists have begun to investigate different groups' perceptions of whether knowledge occurs in Gettier cases. A systematic review (Popiel 2016) found 15 studies published between 2001 and 2016 that carried out empirical research into intuitions regarding Gettier cases. The studies' findings are mixed with some reporting that laypeople's intuitions agree with those of philosophers (e.g. Nagel et al. 2013) whilst others suggest they differ (e.g. Starmans and Friedman 2012). Further research has suggested that attributions of knowledge may vary between members of different cultures (Weinberg et al. 2001) but this finding is disputed (Kim and Yuan 2015), and there is an ongoing methodological debate about how to elicit such intuitions (Jackson 2011; Starmans and Friedman 2013).

Whatever the perceptions of other groups, contemporary epistemologists are reported to believe there are still no 'easy answers' (Pritchard 2016, p. 131) to the challenges that have arisen to the JTB model of knowledge. In the context of science, though it is acknowledged that Gettier cases have undermined the JTB account of knowledge, it has been argued that it is useful to retain the term 'scientific knowledge' to distinguish well-evidenced models from mere beliefs (McCain 2016). Similarly, the term knowledge remains widely used in discussions of learning in science education, and the development of JTBs has been described as the ultimate goal of science education, even though some learners, in certain topics, may only achieve the lesser goals of understanding or acceptance without belief (Siegel 2005; Smith and Siegel 2004, 2016). The next sections consider some imagined situations in science classrooms in which students' claims take the form of JTBs but intuitively seem to fall short of knowledge and discuss the value of reliable belief-forming processes in school science.

4 Gettier Cases in Science Education

In a number of cases in the context of science education, a student's JTB, considered in isolation, might appear to be an instance of successful learning—the student may seem to have acquired knowledge. However, each of the following case described contains the two elements of Gettier cases, fallible justification and lucky truthfulness (Hetherington 2011), and on closer examination, each student's JTB appears to fall short of the status of knowledge.

- Case 1: A teacher asks a student to describe the forces that act on an accelerating rocket and the student replies that a resultant force acts in the direction of motion because all accelerating objects are subject to a resultant force. However, the student's claim is predicated on their pre-formal experiences of the world which have led them to believe that all motion requires the action of a resultant force. Does the student have knowledge of the relationship between force and motion in the case of the rocket?
- Case 2: A student is asked to sketch a graph of the relationship between current and potential difference for an Ohmic conductor and they draw an I-V graph showing a diagonal line passing through the origin which they justify by arguing that current is directly proportional to potential difference. However, the student's answer is based on the belief that current and potential difference are directly proportional for all components. Does the student have knowledge of the relationship between current and potential difference for the Ohmic conductor?
- Case 3: A student is asked to give an example of an unreactive substance and to explain its behaviour. They reply that nitrogen is unreactive because of its full outer shell. However, the student believes that any atom that is isoelectronic with the noble gases, including, for example, the potassium cation, will be unreactive. Does the student have knowledge of the stability of nitrogen?
- Case 4: A student argues that when a 4 V battery is connected to a single bulb, a potential difference of 4 V will be measured across the bulb because there is only one bulb in the circuit and hence the entirety of the battery's EMF will be across the bulb. However, the student believes that potential difference flows round a circuit and is used up by the components it passes through. Do they have knowledge of the potential difference across the bulb?
- Case 5: A teacher asks a student to describe the magnitude of the resultant force acting on a boy standing on the ground. The student replies that the resultant force is zero because the magnitudes of the reaction and gravitational force are equal but they act in opposite directions. However, the student believes that the two forces have equal magnitudes because they comprise an action-reaction pair. Does the student have knowledge of the magnitude of the resultant force acting on the boy?

In each of these cases, though the student possesses a JTB, my intuition is that the student does not possess knowledge because their justifications are fallible but happen to produce a true belief in one context. Such cases can arise when a claim that is true in a limited set of contexts is inappropriately generalised to other situations. A number of alternative conceptions have been linked with the overgeneralisation of a principle (Marbach-Ad et al. 2015; Maskiewicz and Lineback 2013). For example, consider the belief that objects in motion experience a resultant force, as described in case 1 above. In the context of accelerated motion, this belief might be considered to be both justified and true, but in other cases, for example an object travelling at constant velocity, the belief is not true, though a student may feel they are relying on the same source of justification in both cases. The student's JTB in the case of accelerated motion is analogous to the belief in Russell's stopped clock example: the belief is based on a fallible form of justification but is 'lucky' in that it just happens to produce a true belief in one context.

A similar situation occurs in case 2, which describes a student who believes that current is universally proportional to potential difference in components, perhaps because that is what their teacher has implied and what the experiments that they have carried out have shown. The student may make claims that appear to be both justified and true in the case of Ohmic conductors kept at constant temperature, but false if applied in other circumstances, for example to the filament of a lightbulb. This case arises because Ohm's law is a ceteris paribus law, that is, one that is a valid description only if some conditions are met (Cartwright 1980). The third case is also an instance of overgeneralising—a pattern that holds for atoms is applied to ions. In the final two cases, justifications which are generally false happen to lead to true beliefs because of features of the situations to which they are applied.

The cases above suggest that students' claims that appear to be JTBs, in some circumstances, may be based on alternative conceptions of scientific concepts. This observation has two pedagogical consequences for science teachers. First, an approach that can highlight the presence of lucky belief is proposed. Second, it is argued that teachers should carefully consider the criteria they use to assess learning based on students' claims in different contexts.

5 The Value of Reliable Belief-Forming Processes

Cases of epistemic luck in the science classroom occur when a justification that is in general fallible, happens to produce a claim that matches the accepted scientific model in a particular context (for example, the assumption that all moving objects experience a resultant force when applied to the context of accelerating objects). In such cases, a student's claim in the form of a JTB can be based on an alternative conception. In contexts where lucky belief is possible, teachers should adopt criteria in addition to the presence of JTBs to avoid accepting responses that arise from fallible justifications.

In each of the cases discussed above, a student appears to possess a JTB because they had the good fortune to apply a justification that is generally false to a context in which it generates a true belief. Therefore, two strategies may be used to determine if a student's apparently JTB is a case of lucky belief or evidence of knowledge. First, the student can be asked to describe, in general, the contexts to which their belief is applicable. For example, the student who claimed that a resultant force acts on an accelerating rocket might be asked to describe the types of motion caused by the action of a resultant force. If they reply that all moving objects experience a resultant force, the description of the rocket is likely to be a case of lucky belief rather than knowledge. Second, the student's application of the belief to other contexts can be investigated, for example, they might be asked to describe the forces that act on a satellite moving with constant velocity. If the student argues that a resultant force acts on the satellite, the claim in the context of the rocket may be an example of lucky belief.

Both strategies can be used to detect lucky beliefs. The first provides a teacher with information on a student's understanding of the contexts to which a belief applies, and the student's responses may be used to inform teaching that modifies the student's awareness of rules for the application of the belief. For example, the teacher could explain that only accelerating or decelerating objects experience a resultant force. However, a student may be capable of stating a general principle that outlines when a particular belief should be activated but fail to apply that activation rule consistently across contexts. Then, the second approach, which assesses activation across a range of contexts, though time consuming, allows an assessor to determine the reliability of a student's belief-forming processes across a range of contexts (Brock and Taber 2017b) and provide targeted support to alter the activation of beliefs in particular situations.

The two strategies described above cohere with an approach to epistemology, labelled reliabilism, developed in response to the Gettier cases (Goldman 1979). Goldman (1979) argued that knowledge is produced by cognitive processes that reliably produce true beliefs rather than false ones. Processes that usually yield true beliefs are referred to as a reliable belief-forming processes (Alston 1995). I do not claim that reliabilism is a sufficient model of knowledge, as there are a number of reasons to doubt its adequacy (Conee and Feldman 1998). Rather, it is introduced here to illustrate the claim that learners gain epistemic value from possessing reliable belief-forming processes (Goldman 2012) and that supporting students to develop such processes should be an aim of science teaching.

It is important to clarify that, although it is proposed that reliable belief-forming processes themselves are valuable, it does not follow that beliefs produced by reliable processes are more valuable than lucky beliefs. Zagzebski (2003) has argued that reliably produced true beliefs are no more valuable than other true beliefs by drawing an analogy: she argued that a good espresso is good irrespective of the reliability of the espresso machine that produced it. In the context of science education, this argument suggests a JTB about the acceleration of a rocket is equally valuable whether it is produced by lucky or reliable processes. However, whilst the value of a true belief is not enhanced by the manner in which it was acquired, reliable belief-forming processes are epistemically valuable by virtue of their reliability (Goldman 2012). Taking up Zagzebski's analogy, Goldman argued that although the value of an individual coffee is not enhanced by being produced by a reliable espresso machine, a high probability of producing a good espresso is a valuable property of a machine. Similarly, in the science classroom, processes that reliably produce true beliefs should be considered to be epistemically valuable to learners.

A significant epistemic aim of science education, amongst other goals, should be to support students to develop reliable belief-forming processes. The reliability of a learner's belief-forming processes will vary; some processes may produce reliable beliefs in a small number of situations, whilst others may be successful across a wide range number of contexts (Henderson and Horgan 2011). The ability to respond in a reliable manner across a range of contexts is seen as an aspect of expertise (diSessa 2002; diSessa and Wagner 2005; Kuhn and Phelps 1982; Parnafes 2012), though even experts' belief-forming processes may be unreliable under certain circumstances (Goldberg and Thompson-Schill 2009; Kelemen et al. 2013). Whilst it is, in general, challenging to define a definitive set of contexts in which reliable expert performance occurs (Clark 2006; diSessa and Wagner 2005), in the controlled environment of school science classrooms, well-written curricula should specify the types of contexts in which reliable performance is expected from students at different stages of development.

6 Different Criteria for Different Contexts

Though assessing the reliability of belief-forming processes should be an aspect of assessment, at least in contexts where lucky belief is possible, setting reliable belief generation as a criterion for successful learning in all situations in the science classroom is an unrealistic goal. Investigating the reliability of belief-forming processes is time consuming and, in some teaching contexts, weaker assessment data may provide 'good enough' evidence of learning. This pedagogic claim is analogous to the proposal made in contextualist epistemology (Cohen 1987; DeRose 2009) that different criteria may be used to judge the epistemic status of claims in different contexts.

Gettier cases suggest that the JTB model, by itself, is an insufficient account of knowledge. One strategy to produce a more robust model of knowledge is to require criteria in addition to JTB, for example, a JTB must be 'undefeated' (Lehrer and Paxson 1969, p. 225). The undefeated criterion suggests that knowledge occurs when a learner has a JTB and no true statement exists that can 'defeat' the justification. This construction of knowledge allows Gettier cases to be classified as situations that do not represent knowledge, as the justifications proposed in the situations can be defeated. For example, in the case of Russell's stopped clock, the statement that the clock is broken 'defeats' a JTB based on an observation of the clock. Such additional criteria can lead to a situation in which, by stringent epistemological standards, we possess very little knowledge and everyday JTBs ('I know where I parked my car') no longer count as knowledge (Lewis 1996).

It is difficult to produce a model of justification that both defends the JTB model of knowledge against Gettier cases, yet allows everyday empirically justified beliefs to retain their knowledge status (Williamson 2002). One solution to this problem was suggested by contextualist epistemologists (Cohen 1987; DeRose 2009) who proposed that the epistemic criteria by which a sentence may be judged to be knowledge vary depending on the contexts in which the sentence is uttered—knowledge in everyday conversation is judged by different criteria than knowledge in science or in a law court (Stine 1976). A person is judged to know something if they have a true belief and are in a 'good enough epistemic position' (DeRose 2009, p. 3, original emphasis removed) in a particular context.

The preceding description of contextualist epistemology is not intended as an endorsement of its adequacy as a model of knowledge, but is introduced to highlight a similar assumption that is adopted by science teachers when assessing students' claims. Unlike epistemologists, teachers are not necessarily interested in determining whether a student's claim counts as knowledge but are concerned with assessing learning. However, both teachers and philosophers require criteria to make judgements about the value of different kinds of claim. As in contextualism, teachers make (often implicit) adjustments to the criteria they use to judge students' learning depending on the context of assessment. In some situations, a simple true belief may be taken as an adequate response. For example, in reply to the question, 'How does a rocket move?', a student's answer that 'It accelerates', a simple true belief, may be a good enough answer if distinguishing different forms of motion. Teachers often accept true beliefs as responses and it is claimed that students are rarely required to produce strongly justified knowledge claims in the science classroom (Driver et al. 2000; Lemke 1990; McNeill and Krajcik 2008).

Whilst true beliefs are sometimes adequate responses, if students are rarely required to justify their beliefs, the role of justification in scientific knowledge is neglected and students may gain the impression that school science is a 'rhetoric of conclusions' (Schwab 1962, p. 24). Teaching that focuses solely on learning and recalling scientific true beliefs, without justifications, encourages intellectual dependence and is disrespectful of learners' autonomy as knowers (Norris 1997). Though there may be contexts in which a true belief is a pedagogically desirable response, teachers should reflect on the consequences of regularly accepting beliefs without justifications as evidence of learning.

JTBs are seen as a more valuable epistemic state than true beliefs (Zagzebski 2003). For example, following a discussion of Newtonian physics, a claim in the form of a JTB, 'The rocket accelerates because a resultant force acts on it', might be taken as evidence that learning has occurred. Whilst the claim may show some evidence of the student's ability to apply the

Newtonian model of motion, as discussed above, the JTB might be an instance of lucky belief. Additional evidence is required to determine whether the student possesses the ability to reliably form JTBs about accelerated motion by probing their understanding of the relationship between resultant force and motion in general and by investigating the student's application of the belief to other contexts. The intention of this argument is not to deny the value of JTBs in science education because, in general, they are valuable epistemic states, but to highlight that there is additional value in the possession of reliable belief-forming processes (Goldman 2012). Both the development of reliable belief-forming processes and the acquisition of JTBs should be seen as goals of science education. A student who can produce a JTB about the motion of an accelerating rocket has gained a valuable belief; however, the belief may have been produced through a lucky process which does not allow the learner to form true beliefs about the motion of objects in different contexts. In comparison to the activation of a JTB in one context, the ability to reliably form JTBs about the motion of objects across a range of different contexts is a more valuable state.

Therefore, science teachers should carefully consider the kinds of claim that they will accept as evidence that learning has taken place. In some contexts, there are good pedagogic reasons for accepting weak knowledge claims, such as true beliefs. For example, when verifying the presence of previously taught content, a report of a simple true belief may be taken as sufficient evidence of learning. However, even when teachers insist on responses that take the form of a JTB, in some contexts, lucky belief may hide pedagogically significant alternative conceptions. Therefore, teachers should be alert to contexts, like those described above, in which lucky beliefs may occur and, in those cases, seek evidence of reliable belief-forming processes, rather than simple JTBs, as evidence of successful learning. Such an assessment is more time consuming than one eliciting a simple true belief. However, if the development of reliable belief-forming processes is seen as an important goal of science education, assessing and supporting the development of students' belief-forming processes is then a significant aspect of good science teaching and worth the additional time and effort required.

7 'Un-Lucky' Teaching: Developing Awareness of Cases of Lucky Belief

Whilst instances of lucky belief may be relatively rare in the science classroom, they highlight two significant pedagogical issues: the value of reliable belief-forming processes and the importance of defining the types of claims that can be taken as evidence of learning in different teaching contexts.

First, the pressures of external examinations might encourage classroom environments that place a high value on students' ability to recall JTBs in a narrow range of contexts (Roberts 2016). Whilst the acquisition of JTBs is an important aim of learning about science, students may acquire JTBs but fail to apply them in the same manner as expert scientists (Brock and Taber 2017a; Sabella and Redish 2007). Teachers should aim to foster intellectually independent students who can make sense of new situations (Mintzes et al. 1998; Norris 1997) and ideally, good teaching should support students to develop reliable belief-forming processes that generate JTBs across a wide range of contexts.

Second, teachers should consider the criteria that they will use to judge students' learning. As in contextualist epistemology (Stine 1976), teachers may adjust their criteria depending on the pedagogical context but should carefully consider the forms of claim that they will take as evidence of learning. A teacher who decides that a simple true belief is an acceptable response to a question should be aware that students may hold a true belief with a mistaken or limited appreciation of its justification. A teacher who accepts a JTB as evidence of learning should be alert to the possibility that the JTB may be a lucky belief and be based on an alternative conception. As has been suggested above, in contexts where lucky belief is possible, a teacher should ascertain whether a claim in the form of a JTB is the result of a reliable belief-forming process.

If a goal of science education is the development of reliable belief-forming processes, then assessment might be conceptualised as a means by which the reliability of students' belief-forming processes is established. An assertion of a JTB in a particular context represents only a single piece of data, rather than definitive evidence, that a learner possesses a reliable belief-forming process. That students may, on occasion, through epistemic luck, produce a claim that has the form of a JTB but is based on an alternative conception, highlights the challenges that teachers face in establishing the reliability of students' belief-forming processes. It is hoped that emphasising the development of reliable belief-forming processes as a goal of science education, will support teachers' and researchers' approaches to assessing students' learning.

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Compliance with Ethical Standards

Conflict of Interest The author declares no conflict of interest.

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References

Alston, W. P. (1995). How to think about reliability. *Philosophical Topics, 23*(1), 1–29.

Bigelow, J. (2006). Gettier's theorem. In S. Hetherington (Ed.), *Aspects of knowing: epistemological essays* (pp. 203–218). Oxford: Elsevier Ltd..

BonJour, L. (2001). *Epistemology: classical problems and contemporary responses*. Lanham: Rowman & Littlefield Publishers.

Brock, R., & Taber, K. S. (2017a). Making-sense of "making-sense" in physics education: a microgenetic collective case study. In K. Hahl, K. Juuti, J. Lampiselkä, A. Uitto, & J. Lavonen (Eds.), *Cognitive and affective aspects in science education research—selected papers from the ESERA 2015 conference* (pp. 167–178). Dordrecht: Springer.

Brock, R., & Taber, K. S. (2017b). The application of the microgenetic method to studies of learning in science education: characteristics of published studies, methodological issues and recommendations for future research. *Studies in Science Education, 53*(1), 45–73.

Cartwright, N. (1980). The truth doesn't explain much. *American Philosophical Quarterly, 17*(2), 159–163.

Cellucci, C. (2017). *Rethinking knowledge: the heuristic view.* Cham: Springer International Publishing.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1–49.

Chisholm, R. (1966). *Theory of knowledge*. Englewood Cliffs: Prentice Hall.

Clark, D. B. (2006). Longitudinal conceptual change in students' understanding of thermal equilibrium: an examination of the process of conceptual restructuring. *Cognition and Instruction, 24*(4), 467–563.

Cobern, W. W. (1993). College students' conceptualizations of nature: an interpretive world view analysis. *Journal of Research in Science Teaching, 30*(8), 935–951.

Cobern, W. W. (2000). The nature of science and the role of knowledge and belief. *Science & Education, 9*(3), 219–246.

Cohen, S. (1987). Knowledge, context, and social standards. *Synthese, 73*(1), 3–26.

Conee, E., & Feldman, R. (1998). The generality problem for reliabilism. *Philosophical Studies, 89*(1), 1–29.

DeRose, K. (2009). *The case for contextualism: knowledge, skepticism, and context*. Oxford: Oxford University Press.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: issues in theory and practice* (pp. 29–60). Dordrecht: Kluwer.

diSessa, A. A., & Wagner, J. F. (2005). What coordination has to say about transfer. In J. P. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 121–154). Greenwich: Information Age Publishing.

Driver, R., & Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education, 13*(1), 105–122.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education, 84*(3), 287–312.

Foley, R. (2002). Conceptual diversity in epistemology. In P. K. Moser (Ed.), *The Oxford handbook of epistemology* (pp. 177–203). Oxford: Open University Press.

Gettier, E. L. (1963). Is justified true belief knowledge? *Analysis, 23*(6), 121–123.

Goldberg, R. F., & Thompson-Schill, S. L. (2009). Developmental "roots" in mature biological knowledge. *Psychological Science, 20*(4), 480–487.

Goldman, A. I. (1976). Discrimination and perceptual knowledge. *Journal of Philosophy, 73*(20), 771–791.

Goldman, A. I. (1979). What is justified belief? In G. S. Pappas (Ed.), *Justification and knowledge. Philosophical studies series in philosophy* (pp. 1–23). Dordrecht: Springer.

Goldman, A. I. (2012). *Reliabilism and contemporary epistemology: essays*. Oxford: Oxford University Press.

Heathcote, A. (2012). Gettier and the stopped clock. *Analysis, 72*(2), 309–314.

Henderson, D. K., & Horgan, T. (2011). *The epistemological spectrum: at the interface of cognitive science and conceptual analysis*. Oxford: Oxford University Press.

Hennessey, M. N., Karen Murphy, P., & Kulikowich, J. M. (2013). Investigating teachers' beliefs about the utility of epistemic practices: a pilot study of a new assessment. *Instructional Science, 41*(3), 499–519.

Hetherington, S. (2011). The Gettier problem. In S. Bernecker & D. Pritchard (Eds.), *The Routledge companion to epistemology* (pp. 119–130). New York: Routledge.

Hogan, K. (2000). Exploring a process view of students' knowledge about the nature of science. *Science Education, 84*(1), 51–70.

Jackson, F. (2011). On Gettier holdouts. *Mind and Language, 26*(4), 468–481.

Justi, R. S., & Gilbert, J. K. (2002). Science teachers' knowledge about and attitudes towards the use of models and modelling in learning science. *International Journal of Science Education, 24*(12), 1273–1292.

Kelemen, D., Rottman, J., & Seston, R. (2013). Professional physical scientists display tenacious teleological tendencies: purpose-based reasoning as a cognitive default. *Journal of Experimental Psychology: General, 142*(4), 1074–1083.

Kim, M., & Yuan, Y. (2015). No cross-cultural differences in the Gettier car case intuition: a replication study of Weinberg et al. 2001. *Episteme, 12*(3), 355–361.

Klein, P. (1971). A proposed definition of propositional knowledge. *The Journal of Philosophy, 68*(16), 471–482.

Kuhn, D., & Phelps, E. (1982). The development of problem solving strategies. In H. Reese (Ed.), *Advances in child development and behavior* (Vol. 17, pp. 1–44). New York: Academic Press.

Le Morvan, P. (2017). Knowledge before Gettier. *British Journal for the History of Philosophy, 25*(6), 1216–1238.

Lehrer, K., & Paxson, T. (1969). Undefeated justified true belief. *The Journal of Philosophy, 66*(8), 225–237.

Lemke, J. L. (1990). *Talking science: language, learning, and values*. Norwood: Ablex Publishing Corporation.

Lewis, D. (1996). Elusive knowledge. *Australasian Journal of Philosophy, 74*(4), 549–567.

Marbach-Ad, G., Egan, L. C., & Thompson, K. V. (2015). *A discipline-based teaching and learning center: a model for professional development*. Cham: Springer International Publishing.

Maskiewicz, A. C., & Lineback, J. E. (2013). Misconceptions are "so yesterday!". *CBE Life Sciences Education, 12*(3), 352–356.

McCain, K. (2016). *The nature of scientific knowledge: an explanatory approach*. Cham: Springer International Publishing.

McNeill, K. L., & Krajcik, J. S. (2008). Inquiry and scientific explanations: helping students use evidence and reasoning. In J. Luft, R. L. Bell, & J. Gess-Newsome (Eds.), *Science as inquiry in the secondary setting* (pp. 121–134). Arlington: National Science Teachers Association Press.

Mintzes, J. J., Wandersee, J. H., & Novak, J. D. (1998). Preface. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding: a human constructivist view* (pp. 17–20). San Diego: Academic Press.

Moser, P. K. (1985). *Empirical justification*. Dordrecht: D. Reidel Publishing Company.

Nagel, J., Juan, V. S., & Mar, R. A. (2013). Lay denial of knowledge for justified true beliefs. *Cognition, 129*(3), 652–661.

Norris, S. P. (1997). Intellectual independence for nonscientists and other content-transcendent goals of science education. *Science Education, 81*(2), 239–258.

Novak, J. D. (1990). Concept mapping: a useful tool for science education. *Journal of Research in Science Teaching, 27*(10), 937–949.

Osborne, R. J., & Wittrock, M. C. (1983). Learning science: a generative process. *Science Education, 67*(4), 489–508.

Parikh, R., & Renero, A. (2017). Justified true belief: Plato, Gettier, and Turing. In J. Floyd & A. Bokulich (Eds.), *Philosophical explorations of the legacy of Alan Turing* (pp. 93–102). Cham: Springer.

Parnafes, O. (2012). Developing explanations and developing understanding: students explain the phases of the moon using visual representations. *Cognition and Instruction, 30*(4), 359–403.

Plantinga, A. (1993). *Warrant: the current debate*. Oxford: Oxford University Press.

Plato. (1992). *Theaetetus*. (B. Williams, Ed., M. J. Levett, Trans.). Indianapolis: Hackett Publishing Company.

Popiel, M. (2016). *A systematic review of studies using Gettier-type thought experiments*. Master of Arts Thesis, University of Denver. Retrieved from https://digitalcommons.du.edu/etd/1216/

Pritchard, D. (2005). *Epistemic luck*. Oxford: Oxford University Press.

Pritchard, D. (2016). Part IV: Epistemology. In D. Pritchard (Ed.), *What is this thing called philosophy?* (pp. 121–158). Abbingdon: Routledge.

Roberts, R. C. (2016). Are some of the things faculty do to maximize their student evaluation of teachers scores unethical? *Journal of Academic Ethics, 14*(2), 133–148.

Russell, B. (1912). *The problems of philosophy*. London: Williams & Norgate.

Russell, B. (1948). *Human knowledge*. New York: Simon and Schuster.

Sabella, M. S., & Redish, E. F. (2007). Knowledge organization and activation in physics problem solving. *American Journal of Physics, 75*(11), 1017–1029.

Schwab, J. J. (1962). *The teaching of science as enquiry*. Cambridge: Harvard University Press.

Siegel, H. (2005). Truth, thinking, testimony and trust: Alvin Goldman on epistemology and education. *Philosophy and Phenomenological Research, 71*(2), 345–366.

Sinatra, G. M., Southerland, S. A., McConaughy, F., & Demastes, J. W. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. *Journal of Research in Science Teaching, 40*(5), 510–528.

Smith, M. U., & Siegel, H. (2004). Knowing, believing, and understanding: what goals for science education? *Science & Education, 13*(6), 553–582.

Smith, M. U., & Siegel, H. (2016). On the relationship between belief and acceptance of evolution as goals of evolution education: twelve years later. *Science and Education, 25*(5–6), 473–496.

Southerland, S. A., Sinatra, G. M., & Matthews, M. R. (2001). Belief, knowledge, and science education. *Educational Psychology Review, 13*(4), 325–351.

Starmans, C., & Friedman, O. (2012). The folk conception of knowledge. *Cognition, 124*(3), 272–283.

Starmans, C., & Friedman, O. (2013). Taking "know" for an answer: a reply to Nagel, San Juan, and Mar. *Cognition, 129*(3), 662–665.

Stine, G. C. (1976). Skepticism, relevant alternatives, and deductive closure. *Philosophical Studies, 29*(4), 249–261.

Taber, K. S. (2013). *Modelling learners and learning in science education: developing representations of concepts, conceptual structure and conceptual change to inform teaching and research*. Dordrecht: Springer.

Turri, J. (2012a). In Gettier's wake. In S. Hetherington (Ed.), *Epistemology: the key thinkers* (pp. 214–229). London: Continuum.

Turri, J. (2012b). Is knowledge justified true belief? *Synthese, 184*(3), 247–259.

Turri, J. (2013). A conspicuous art: putting Gettier to the test. *Philosophers' Imprint, 13*(10), 1–6.

Turri, J. (2016). Knowledge judgments in "Gettier" cases. In J. Sytsma & W. Buckwalter (Eds.), *A companion to experimental philosophy* (pp. 337–348). Chichester: Wiley Blackwell.

Weinberg, J. M., Nichols, S., & Stich, S. (2001). Normativity and epistemic intuitions. *Philosophical Topics, 49*(1&2), 429–460.

Williamson, T. (2002). *Knowledge and its limits*. Oxford: Oxford University Press.

Zagzebski, L. (2003). The search for the source of epistemic good. *Metaphilosophy, 34*(1–2), 12–28.