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ARTICLE

Risk in Science Instruction

The Realist and Constructivist Paradigms of Risk

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Abstract Risk is always present in people's lives: diseases, new technologies, socio-scientific issues (SSIs) such as climate change, and advances in medicine—to name just a few examples—all carry risks. To be able to navigate risks in everyday life, as well as to participate in social debate on risk-related issues, students need to develop risk competence. Science education can be a powerful tool in supporting students' risk competence, which is an important component of scientific literacy. As there are different definitions of risk within the scientific community, the aims of this article are (1) to review the literature on two major theoretical frameworks for conceptualising risk, the realist, and the constructivist paradigms of risk and (2) to connect both in order to suggest a working definition of what can be understood as risk competence in science instruction.

1 Introduction

Modern society is continuously confronted with risks related to new developments in science and technology. Through both media coverage and personal decision-making, people encounter risk-related controversies in their daily lives.

In a wider context, risk-related issues (RRIs) are debated in politics and are subject to decision-making procedures in democratic societies. Often, RRIs attract national attention, stem from recent developments in science and technology, and are discussed as controversies within the science community itself. Examples of these RRIs are the uses of genetically modified organisms (GMOs) in agriculture and medicine and the use of nanoparticles in food. Although developments in science and technology undoubtedly bring benefits, such as increased life expectancy, sufficient food and water stocks, and global communication networks, social theorists have recently argued that the products

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of scientific and technological research also challenge people by introducing new uncertainties and risks. Thus, societies have become risk societies.[1]

New technological developments carry risks for individuals and for society as a whole.[2] Whilst some risks are rarely encountered, others occur on a daily basis, forcing people to make frequent decisions about RRIs (Bodemer and Gaissmaier 2015; Knoll et al. 2015). As products of scientific knowledge, new technologies also often entail risks. It is neither possible nor desirable to avoid these risks entirely, and people must therefore be able to cope with them. The problem arises when some risks—particularly those that trigger emotionally charged reactions—are overestimated, whilst others are underestimated and their potentially fatal consequences ignored. Still, risks are entangled with people's lives, and risk management has an important role in modern society (Fischhoff 1983; Hopkin 2017). Whilst governments and organisations employ experts to perform risk assessments in various fields, laypeople also need to be able to manage risks. However, this requires that they both understand experts' risk assessments and be able to assess risks themselves.[3] Modern democracies depend upon well-informed laypersons, who have a powerful impact on political decisions regarding RRIs (Kolstø 2001). Thus, laypeople's abilities to make informed decisions and defend their viewpoints are important, both individually and socio-politically (Cullipher et al. 2015; Klebl and Borst 2010). Engaging in such debates and managing risks requires risk competence, i.e. the ability to identify risks, evaluate options, assess benefits and costs in diverse scenarios, and come to a conclusion or decision.

Science education needs to prepare students to participate in society as scientifically literate citizens (Laugksch 2000). An important aspect of scientific literacy is the ability to identify risks, assess them, and engage in debates about RRIs (Jenkins 1990; Ryder 2001). The ability to assess risks is thus an essential aspect of scientific literacy. A recent study by Kolstø (2006) has shown that risk information has a notable impact on decision-making processes concerning socio-scientific issues (SSIs), which often revolve around topics that involve RRIs—for example, expert disagreement about the impact of risk on humans and the environment. Many educational organisations hold the view that scientific literacy comprises the ability to make informed decisions about these issues.[4] Over the course of the last 40 years, the recommendation to introduce risk assessment into science education has appeared in the science education literature[5] and in educational programs.[6]

This article aims to offer a literature review on the topic of risk, focusing on two major theoretical frameworks: the realist and the constructivist paradigms of risk. The second aim of the article is to draw on both paradigms to suggest a working definition of risk competence and to discuss its core components. Ultimately, this article aims at providing

[1] In 'Risk society: towards a new modernity' (1992), Ulrich Beck predicts a growing number of risks. While humans have always had to face risks, Beck's thesis is that members of modern society are increasingly challenged with man-made risks, which are the results of technologies and products usually connected with new scientific knowledge.

[2] cf. Slovic et al. (1982), Finucane and Holup (2005), and Gigerenzer (2006).

[3] See Bond (2009), Gigerenzer and Martignon (2015), and Latten et al. (2011).

[4] See, for example, Royal Society (1985), AAAS (1989), NRC (1996), and OECD (1999).

[5] The first proposal to include risk assessment in science education was probably made by Howes (1975) and, 10 years later, by Eijkelhof (1986).

[6] For the USA, see Science Education for Public Understanding Program (2011); in Australia, see Australian Curriculum, Assessment, and Reporting Authority (2016); and in the UK, see Standards and Testing Agency (2013).

educators with ways to explicitly discuss risk in science classes and support students in developing risk competence.

2 Risk in the Science Education Literature

The science education literature has long supported the idea of addressing aspects of uncertainty in the science classroom. Ravetz (1997, p. 7) emphasised the importance of uncertainty, claiming that "[…] the certainty of science is much less absolute than generations of teachers have assumed and implicitly taught". One of the dimensions of the nature of science (NOS), according to a Delphi study conducted by Jason Osborne and colleagues, is 'science and certainty', which suggests that scientific knowledge is tentative (subject to change) and that it lacks certainty, for example "simply because experiments have yet to be undertaken" regarding controversial issues such as GMOs (Osborne et al. 2003, p. 708). Including issues of uncertainty, as well as using social and cultural contexts in science teaching, results in what Roberts (2007) has described as 'Vision II' of scientific literacy. His 'Vision I' comprises scientific methodology and scientific knowledge, whilst 'Vision II' expands this view by including the uncertainty that often underlies scientific research and the perspective of science as a social practice. Cross (1993) has argued for an integration of risk as a feature of scientific literacy:

> It is the conception of scientific literacy that is at the heart of proposed changes. One component that appears to have been only recently recognised is the importance of risk assessment and risk management in social issues surrounding science and technology. (Cross 1993, p. 171)

He further suggested that risk assessment and management are a chance for science instructors to present scientific research as a social activity and discuss not only scientific methodology but also value judgements and issues of uncertainty within the science community.

One of the first publications to argue for including risk and risk assessment in science teaching was written by Howes (1975), who illustrated the importance of teaching risk assessment in the context of low-level radiation and stressed the relevance of open discussions about the limitations of scientific practice. Ten years after Howes' publication, Eijkelhof (1986) took up the issue and highlighted the reasons for adopting risk assessment—especially with regard to identifying (un)acceptable risks—into science curricula. Like Howes, Eijkelhof discussed the social aspects of risk assessment that arise independently of scientific practice. Values and ethical questions cannot be excluded when teaching risk assessment and management in science classes. Just like the evaluation of scientific facts, values and ethics play a role in risk assessment and management. Furthermore, Eijkelhof presented a teaching unit on ionising radiation, proposing the following arguments:

1. Values and ethical questions of both a personal and a social nature cannot be avoided in science teaching.
2. Science teaching should be extended to include skills that are essential to the processing of scientific and technological information of personal and social use.
3. Students should have an understanding of the following topics:

    a. How to make decisions by selecting policies for action amongst alternatives,
    b. What risk means,

   c. How preferences, ethics, and values influence judgement.
4. A major fraction of science courses should be organised in terms of problems—some societal, some personal.[7]

In subsequent years, proposals in favour of incorporating the topic of risk into science classes have been discussed by several authors.[8] At least one critical publication cautions against the 'humanising' of science classes and questioned whether risk should be added into UK's national curriculum (Donnelly 2006).

To address RRIs in science classes, science education must depict science in a way that shows not only its merits but also its limitations and uncertainties (Cross 1993; Jenkins 2000). Using SSIs is one way to approach aspects of science that have already been discussed by many authors.[9] SSIs are "controversial social issues with conceptual, procedural, or technological ties to science" (Sadler and Donnelly 2006, p. 1463). The scientifically contested nature of these problems, in combination with their social and cultural aspects, suggests a close affiliation with risk-related problems. One influential study, which directly addresses the aspect of risk in SSIs, is Kolstø's (2006) study concerning argumentation and decision-making strategies related to the safety of high-voltage power lines. Over the course of that study, students were asked to make a decision about the construction of high-voltage power lines, and they were provided with geographical, political, and economic information. Additionally, the students received the results of a scientific risk assessment of the health risks of such power lines. Kolstø was able to show that the influence of the risk assessment information on the students' decision-making process was substantial, and he concluded that teaching is crucial for providing students with knowledge about the concepts of risk and uncertainty. Whilst the aspect of risk has been addressed previously within SSIs, the present article focuses on risk and its different concepts within the realist and constructivist paradigm and proposes core components of risk competence.

Various curricula, standards, and policy documents in science education already include the topic of risk; that is, they aim to foster the abilities to recognise risks associated with scientifically contested issues and design solutions with the help of cost and risk-benefit analyses. Risk and risk-cost-benefit analyses are mentioned in policies concerning science education in the UK (DfE 2014a, b), in the USA (NRC, The National Research Council 1996, 2012; NGSS Lead States 2013), Canada (OME, Ontario Ministry of Education 2008a, b), and Australia (ACARA 2015). In German educational standards for biology, the concept of risk is addressed only very briefly in the introductory chapter, but is not mentioned further in subsequent chapters (KMK 2005a). The same is true for the standards for chemistry, physics, and mathematics (KMK 2005b, c, d). In the Programme for International Student Assessment (PISA) of the OECD countries, risk, benefit, and cost are included in several of the evaluated categories in science teaching, such as 'technology systems' and 'hazards' (Bybee and McCrae 2009; OECD 2013).

[7] Eijkelhof's work not only promoted the inclusion of risk in science education but also advanced the STS (science-technology-society) movement of the 1980s and early 1990s.
[8] For example, see Howes (1975), Eijkelhof (1986, 1990, 1996), Keren and Eijkelhof (1990), Lijnse et al. (1990), Cross (1993), Ravetz (1997), Jenkins (2000), Dillon and Gill (2001), Levinson and Turner (2001), Solomon (2003), Bryce and Gray (2004), and Christensen (2009).
[9] For example, compare with Fleming (1986a, 1986b), Solomon (1990), Zeidler et al. (2002), Dawson and Venville (2010), Khishfe (2013), and Lee et al. (2013).

3 Concepts of Risk

Human beings have always been exposed to risks. The term risk itself, however, is loosely defined, and the underlying ideas of risk are ambiguous. Lack of definitional precision can be observed in everyday language, where the term is used interchangeably and synonymously with other terms, such as hazard, peril, and danger. Public understanding of risk, therefore, may reflect these ambiguities. Furthermore, definitional coherence is rendered problematic because modern concepts of risk are used in many academic disciplines, with a variety of definitions that differ not only across but also even within disciplines (Bodemer and Gaissmaier 2015). This section aims to outline the differing concepts of risk used in science contexts.

3.1 Reality and Possibility

All concepts of risk share one common feature: a distinction between reality and possibility (Evers and Nowotny 1987; Markowitz 1991; Renn 1992). In addition, the assumption that future events are neither predetermined nor controlled by fate is relatively new in history (Renn 1992). Risk depends upon the distinction between reality and possibility, as it is impossible to take risks if the outcomes of human activities are fixed and immutable. For example, a fatal traffic accident can be seen as a predetermined event in a person's life, such that his or her death is considered inevitable. Or, if one assumes that the future is undetermined, traffic accidents can be seen as only one of many possible future events, the occurrence of which can be avoided or at least mitigated by certain measures, such as introducing speed limits.

Risk came into existence as soon as the future was understood as unwritten and with a multitude of possible outcomes. Risk refers to the possibility of an outcome occurring that is undesirable and entails negative effects (Covello and Merkhofer 1993, p. 2). The assumption of an undetermined future, furthermore, implies that human activity in the present can influence or avoid undesirable outcomes in the future by addressing the causal mechanisms leading to negative effects. The varying concepts of risk all share this assumption but differ in their definitions of negative outcomes, measurement of probabilities and uncertainties, and underlying conceptualisation of reality (Renn 1992).

3.2 Realist and Constructivist Paradigms

Whilst all risk concepts operate upon the distinction between reality and possibility, they can be further differentiated into two higher-order paradigms. Rosa (1998) wrote about of *positivistic* and *constructivistic* paradigms, Renn (1998b) referred to them as *realist* and *constructivist* paradigms, and Singleton et al. (2009) called them *realist* and *social constructivist* paradigms. In this article, the two frameworks will be referred to as realist and constructivist paradigms, respectively.

The *realist paradigm* of risk stems from the ontological theory of realism (or objectivism). Realism assumes the existence of a world that is independent of human observers. This assumption of an 'objective' world, divorced from human existence, can be seen as the basic presupposition of science (Rosa 1998). Science is based on a realist view of the world insofar as it assumes that there is an external, independent world that is amenable to systematic inquiry and can be known by humans, even if not perfectly.[10] The *constructivist paradigm* of risk, in contrast, is based on the denial of the realist view of the external world (Renn 1998b; Rosa 1998). Its advocates claim that a definite interpretation of the world's attributes is impossible, as all knowledge is subject to re-interpretation. Thus, distinguishing between the world and human interpretations of the world is considered impossible (Rosa 1998).

3.3 The Realist Paradigm of Risk

The realist paradigm of risk is particularly prevalent in the natural sciences, medicine, engineering, and physics (Renn 1998a; Singleton et al. 2009). Within the realist paradigm, risk is understood as a tangible and quantifiable characteristic of an event (Jasanoff 1998; Plapp 2004). Whilst the technical and scientific communities employ a range of different approaches to measure risk, two main factors are generally agreed upon when describing risk, which are the probability of harm and the severity of harm in case of the event.[11] Risk is conceptualised as the multiplication of those two factors (see risk formula in Fig. 1) (Slovic 2001).

In this context, harm is understood as physical harm to organisms or ecosystems and loss of life. Methods of the realist paradigm seek objectivity by using explicitly defined procedures to measure risk (Kasperson et al. 1988). These procedures are defined by rigorous processes that are evaluated and established through peer review and offer a commonly agreed upon framework (Singleton et al. 2009). In the realist paradigm, there are three main risk assessment methods: the actuarial approach, the toxicological/epidemiological approach, and the engineering approach (Renn 1992; Singleton et al. 2009).[12] These three main methods within the realist paradigm all define negative events as physical harm to humans or ecosystems, average these events over time and space, and use relative frequencies to specify probabilities of negative events in the future (Renn 1992). Examples of this approach include the prediction of the frequency of airplane crashes for the upcoming year by extrapolating the estimated number from the number of crashes in the previous year, or assessing health risks based on controlled trials for testing new medical substances. The aim of these methods is to identify risks and their causes in order to avoid and mitigate these causes and, accordingly, their negative effects (Morgan 1990). Because they are part of a scientific approach, realist methods exclude emotional aspects, such as the value judgements of researchers (Plapp 2004).

3.3.1 Implications for Science Education: the Realist Paradigm in the Science Classroom

In order to manage risks and assess the likelihood of their personal impact, students need to be able to make sense of the results of experts' risk analyses. Information about RRIs, which can be found in the media and in informational brochures, for example, often consists of a presentation of (simplified) results of scientific studies. A person's ability to understand the presented data is integral to their subsequent decision-making about the respective RRI. As an example of the presentation of medical data in information booklets targeting the lay public, consult Fig. 2 with data on the probability of positive and false positive results of

[10] An in-depth look at science and the theory of realism can be found in the comprehensive work of Bhaskar (2008): A Realist Theory of Science.
[11] Compare Short (1984), Covello and Merkhofer (1993), Geiger (1998), and Brewer et al. (2007).
[12] For a more detailed review of realist methods, consult Renn (1992, pp. 58–61).

$$R = P \times S$$

R = risk, P = probability of harm, S = severity

Fig. 1 Risk formula after Renn (1992), Geiger (1998), Singleton et al. (2009), and Wachinger et al. (2013)

mammographic screening for breast cancer. An understanding of basic statistics and probability is necessary in order for students (and patients) to be able to understand such a booklet. In the example shown in Fig. 2, the probability of receiving a positive result is 30 out of 1000 (3%), and the probability of receiving a false positive result is 24 out of 1000 (2.4%). Considering only patients who received a positive result, the probability of this result being a false positive one is 24 out of 30 (80%). Understanding these (basic) mathematical statistics is crucial for developing the ability to read and understand data on RRIs as they are often presented in media.

Gigerenzer and Martignon (2015) have argued for teaching statistics and probability theory early on in science curricula to support the development of students' risk competence. Latten et al. (2011) have recommended teaching basic statistics and probability as early as primary school. Several authors have supported the idea of strengthening students' ability to understand statistical information (DeHaan et al. 2008; Gal 2012; Garfield and Gal 1999; Till 2014). Whilst these authors proposed the introduction of statistics and probability early on in math curricula, the importance of including statistics and probability in biology, chemistry, and physics curricula is also irrefutable.

Aside from a basic understanding of statistics and probability, students also need scientific knowledge of the specific RRI. In the example above (Fig. 2), the required scientific knowledge is knowledge of the aetiology and pathology of breast cancer as well as knowledge about the methods used for early detection of breast cancer (and their sources of error). The relationship between probability concepts and scientific knowledge is pertinent because students often do not use scientific knowledge in their assessments of risk.[13] Students who master both aspects—statistics/probability and scientific knowledge—are able to read experts' risk assessments, which offer the results of an application of realist methods. A short summary of both aspects can be found in Fig. 3.

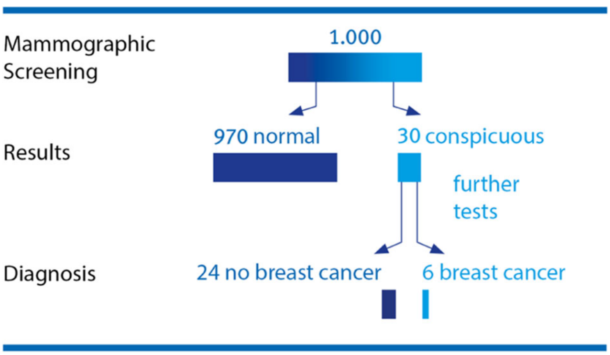

Fig. 2 Probability of conspicuous results after mammographic screening and rate of false positive results (after Deutsche Krebshilfe (2016), p. 19; author's translation)

[13] This has been noted by Kolstø (2006).

Scientific knowledge and statistics/probability

- Knowledge concerning the risk-related topic (such as breast cancer screening, nanotechnology)
- (Basic) understanding of statistics/probability , understanding of probability calculations in order to be able to comprehend the results of experts' risk analyses
- Judgement about the reliability of data

Fig. 3 Essential elements of understanding and assessing risks (part 1)

3.3.2 Critiques of the Realist Paradigm of Risk

Whilst risk assessment methods based on the realist paradigm are widely used, they are not without their critics and have encountered opposition, especially from the social sciences (Douglas 1985; Hoos 1980). Critics claim that the realist paradigm is limited by its narrow definition of what constitutes a negative event (Renn 1992).

The scientific and technical communities reduce risk to the product of the probability of the negative event times its severity; negative events are defined as physical harm whilst severity can be defined by the extend of harm, i.e. how many people got harmed. However, people's perception of undesirable or negative events is much broader than simply physical harm. Moreover, realist methods provide risk assessments on the basis of aggregated data over large segments of the population (Renn 1992), whilst individuals may face different degrees of risk (Beck 1992). One person may be exposed to risk to a greater extent than an average person and, as a consequence, may object to any risk policies based on averaged data (Renn 1992). The aim of realist methods is to reduce risk in proportion to the expected harm (Morgan 1990), but social actions to cope with risk are not limited to simply minimising risk, as they include other objectives such as equity, fairness, or flexibility (Nowotny and Eisikovic 1990; Short 1984). As such, some critics argue that the strong influence of science on risk policy-making provides too much power to an elite group (Jasanoff 1998).

In sum, realist methods to measure risk are valuable and highly useful in their respective fields, but their framework is not sufficient as a single criterion for identifying, assessing, and managing risk. Risk cannot be confined solely to realist explanations according to critics (Short 1989).

3.4 The Constructivist Paradigm

In contrast to the realist paradigm, which aims to objectify risk, the constructivist paradigm of risk takes the subjective perspective into consideration (Singleton et al. 2009). Historically, this paradigm was developed after the realist framework was shown to neglect certain aspects of the impact of hazardous activities and was thus unable to represent the public's perspective on risk (Kasperson et al. 1988), problems that have been recognised by many authors.[14]

[14] See, for example, Covello and Merkhofer (1993), Breakwell (1994), Wilkinson (2001), Rohrmann (2005), Lupton and Tulloch (2002a), Lupton and Tulloch (2002b), and Sjöberg (2004).

Within the constructivist paradigm, risk is not seen as a measurable property of reality but rather as a construct that has its origins in the human mind (Hansson 2010). In this constructivist understanding, risk is referred to as *risk perception* to account for its subjective nature as a mental model that helps people understand, cope with, and manage risks in an uncertain world.[15] Risk perception is an intuitive process, used as a heuristic tool to assess risks without resorting to the elaborate technical risk analyses used by the realist methods (Banse and Bechmann 1998; Plapp 2004). The mental concept of risk is linked with reality via the experience of negative effects or harm (Kasperson et al. 1988; Singleton et al. 2009).

In contrast to the realist definition of negative events as physical harm, the constructivist paradigm's understanding of negative events is much broader (Christensen 2009). Furthermore, risk perception is not limited to and defined by the likelihood of occurrence and the severity of the negative event. People are able to make risk judgements even if these two factors are unknown. The constructivist paradigm views risk not as a one-dimensional, singular objective characteristic but as a multidimensional event (McDaniels 1998; Slovic 1999).

People's belief systems, attitudes, judgements, information processing pathways, values, evaluations of cost-benefit balance, feelings, familiarity with a hazard, emotional and affective reactions, and the framing of media reports are all factors that have weight in the generation of risk perception.[16] Risk perception is further influenced by a person's wider social and cultural background (Burgess 2015; Douglas and Wildavsky 1983). As such, risk perception emerges through a complex interaction of affective and cognitive processes, strongly influenced by individual, cultural, and social characteristics (Gardner and Jones 2011).

Considering the subjective aspect of risk perception, a person's own estimate of risk can diverge significantly from the statistically established probability of the harmful event (Oltedal et al. 2004), and a gap between experts' and laypeople's opinions concerning a hazard source may be observed.[17] The constructivist paradigm seeks to understand this gap and the way risk perception forms in people's minds. It is not to be seen as a replacement for the realist methods of measuring risk, but rather as an expansion that illuminates additional dimensions.

There are several methods used in risk research that seek to measure risk perception in its constructivist understanding, in particular the economic method and the psychometric paradigm. All these methods have in common their rejection of the existence of one risk formula (see Fig. 1), but they differ in their further contextualisations and conceptualisations of risk (Plapp 2004). Depending on their theoretical and historical origins, these methods have each their own definition of risk perception.

Risk concepts within the constructivist paradigm share the view that the causes and consequences of risk are induced by social and cultural processes. Amongst constructivist methods, the *economic methods* are most closely related to the realist methods, but the two differ in that the economic methods expand the realists' underlying definition of an undesirable outcome (Renn 1992). All realist methods define the undesirable outcome of a risk situation as physical harm or loss of life. The economic methods transform this into subjective utilities with a base unit of the degree of satisfaction and dissatisfaction (Walliser 2008). In other words, the economic methods do not strictly specify certain

[15] Compare Sjöberg (2004), Slovic et al. (2007), Metzner-Szigeth (2009), Singleton et al. (2009), and Bodemer and Gaissmaier (2015).

[16] Compare with Trumbo (2002), Oltedal et al. (2004), Sjöberg (2004), and Slovic et al. (2007).

[17] See Sjöberg et al. (2004), Betsch et al. (2012), Bodemer et al. (2014), and Bodemer and Gaissmaier (2015).

outcomes as undesirable (e.g. physical harm), but measure the outcome of a risk situation according to subjective satisfaction. Theoretically, physical harm and loss of life can be defined as a positive outcome.[18]

The social sciences offer multiple explanations of how people's risk perception is shaped. Whilst these explanations are very diverse,[19] all *social and cultural theories* of risk aim to describe the formation of risk perception as a process mediated by cultural and social pressures (Renn 1992). Social and cultural theories of risk share no clear joint concept of risk other than the assumption that humans perceive the world (including its risks) through a lens formed by social and cultural interpretations (Dietz et al. 2002).

Whilst social and cultural methods approach risk by seeking to understand the societal and cultural institutional structures that ultimately shape people's perception of risk, the *psychological perspective* on risk starts at the level of the individual (Zinn and Taylor-Goodby 2006). Psychological methods focus on understanding personal preferences and heuristics in order to explain risk perception at a personal level and predict people's reactions to risks (Renn 2008; Simon 1955; Tversky and Kahneman 1975). Amongst psychological methods, one of the first and most influential models used to measure risk perception is the *psychometric paradigm* (Fischhoff et al. 1978).

The psychometric paradigm deploys psychophysical scaling to measure the perceived risks of various technologies and activities (Slovic 1987), and identifies risk characteristics that contribute to the formation of risk perception (Slovic et al. 1982). Examples of such risk characteristics are knowledge about risk, control over risk, and perceived dreadfulness (Fischhoff et al. 1978; Slovic 1987; Slovic et al. 1982). Participants rate each technology and activity with regard to these risk characteristics and perceived riskiness. The risk characteristics are then clustered through factor analysis to identify higher-order factors influencing risk perception, which can be depicted as a cognitive map consisting of group data on the technologies and activities (as an example, see Fig. 4 after Fischhoff et al. 1978). The placement of each technology or activity within the factor space reflects its score on each of the main factors.

In Fig. 4, nuclear power loads high on both factors, called dread risk and unknown risk by the authors (Fischhoff et al. 1978). This is to say that people connect nuclear power with the risk characteristics of the feeling of dread, loss of personal control, and high catastrophic potential combined with possible high loss of human life (factor 1; after Fischhoff et al. 1978). Additionally, they judge it as an unobservable and new risk with delayed consequences (factor 2; after Fischhoff et al. 1978). The high factor loadings are, in turn, correlated with a high perceived risk of nuclear power. On the other end of the spectrum is the risk of riding a bicycle (see Fig. 4 in the lower left quadrant). People judge this risk as controllable, with a low catastrophic potential and few fatal consequences, illustrated by the fact that bicycles do not load high on either factor. In turn, riding a bicycle is not seen as a very risky activity. Thus, the psychometric paradigm provides a quantitative representation of people's assessment of risk.

[18] For further information on subjective utilities (e.g. subjective (dis)satisfaction) and choice rules under uncertainty within economic calculations, consult Walliser (2008), especially Sect. 3.4 on pp. 56–59.

[19] Prominent examples of cultural and social theories are Beck's (1992) risk society, Giddens' (2011) reflexive modernisation, the theory of communicative action by Habermas (1984, 1987), governmentality by Foucault (1983), and the Cultural Theory of Risk by Douglas (1966) and Douglas and Wildavsky (1983). For a comprehensive overview of social and cultural theories of risk, see Zinn and Taylor-Goodby (2006).

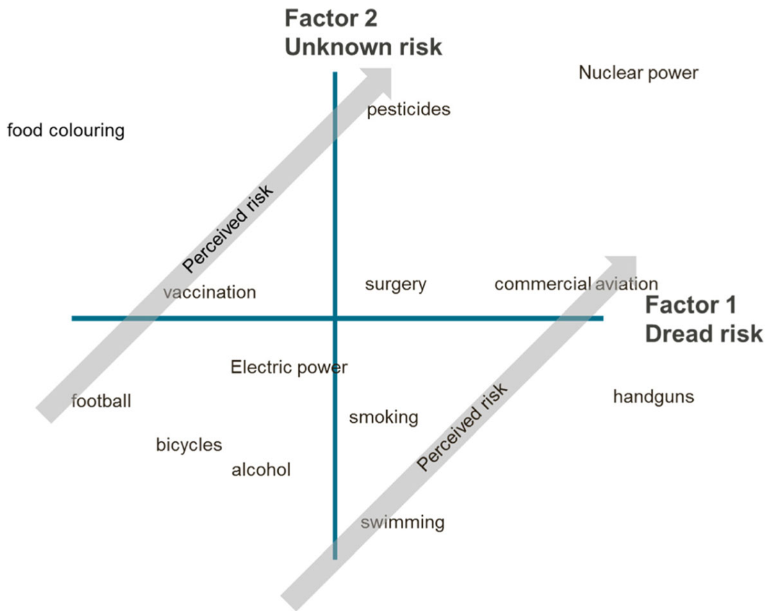

Fig. 4 Depiction of a cognitive map; the axes visualise the factors whilst the factor space spans between them: factor 1 is called dread risk and factor 2 is called unknown risk; perceived risk is depicted as the grey arrows, indicating an increase in perceived risk towards the upper right side of the figure; and several risk sources can be observed within the cognitive map (modified after Singleton et al. (2009) and Slovic (1987))

3.4.1 Implications for Science Education: the Constructivist Paradigm in the Science Classroom

If risk was an objective and measurable feature of a situation, technology, or activity, then teaching about risks would need to focus exclusively on expert opinion and statistical approaches to solve risk problems (Levinson et al. 2012). Technical risk measurement methods, which are used in the STEM field, follow this approach and quantify the actual risk (understood as a measurable feature of reality) by defining risk as the product of the probability of the occurrence of a negative event and the extent of expected damage (Fischer 2009, p. 56). One might draw the conclusion that if students' risk perception deviates from this type of technical risk assessment and that deviation is due to misjudgements, lack of knowledge, or inadequate heuristics, it can be corrected by carrying out appropriate cognitive adjustments to approximate the actual risk (AQA 2016). As such, the purposes and aims of teaching RRIs in science classes would be to assist students in overcoming their (faulty) risk perceptions and to promote cognitive adjustment through teaching approaches that help students assess the actual risk (see Fig. 5).

Whilst this pragmatic understanding of risk does consider uncertainties intrinsic to the methods of applied science, it is a reductionist approach insofar as it simplifies risk to only two components: the probability of a negative event and the severity of that event. As Levinson et al. (2012) stated, "it is relatively, and possibly deceptively, easy to decide on a course of

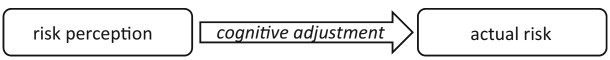

Fig. 5 Risk perception and actual risk (Levinson and Turner 2001)

action, where both the possible outcomes and probabilities for each of these potential outcomes are known" (p. 216). Whilst the risk of losing a poker game can be assessed this way and calculated in a teaching unit on probability theory in math class, this narrow definition of risk does not take into account the complexity of real-world risk issues. Many real-world situations are accompanied by aspects of uncertainty that exceed the simple methodological uncertainties of applied science (inherent in realist methods of assessing risk) and stem from the complexity of the risk-related issue, the disputability of many results in frontier science, and the role science plays in society (Christensen 2009; Ravetz 1997). The ramifications of climate change, the carcinogenic effect of aluminium salts as the active anti-perspirant agent in underarm cosmetics, and the impact of consuming GMOs are examples of contested results in the science community, where different experts' opinions and realist assessments of risk are in conflict. Technical approaches to measuring the objective, actual risk fail to account for the uncertainties and unknowns that accompany new technologies (Singleton et al. 2009).

Two dimensions of uncertainty within the acquisition and application of scientific knowledge are important with regard to RRIs: Uncertainty arising from the complexity and uncertainty of frontier science (Christensen 2009; Howes 1975; Ravetz 1997). RRIs are often highly complex, with a great number of interactive variables that have a direct or indirect influence on the issue. Simple causal relationships, controlled by a few variables—as are often presented in school science—rarely occur in a real-world context. This results in students overestimating the importance of simplified cause-effect relationships (Christensen 2009). However, it is very probable that in a real-world context, students will encounter more highly complex RRIs than the simplified cause-effect relationships taught in science class. These complex issues are accompanied by the uncertainty that emerges from the challenge of accessing and connecting knowledge and information. Uncertainty encompasses the status of (scientific) knowledge—or the lack thereof—as well as an awareness of the unpredictable or unknowable nature of a subject or issue.

Whilst this type of uncertainty can be referred to as epistemological, stressing the limitations of knowledge, there is another type of uncertainty that is ontological in nature (Barnett 2009). Ontological uncertainty describes the "moment of insecurity or even anxiety" (Barnett 2009) that occurs when encountering complex and insufficiently known issues. The second aspect of uncertainty comes from the contested nature of new scientific knowledge. Scientific research and its findings are frequently accompanied by differing experts' opinions and contradictory interpretations of data.[20] New technologies can be discussed as controversies, and their associated risks may be disputed within the scientific community (Colucci-Gray et al. 2006; Sadler and Zeidler 2009). This uncertainty, stemming from the complexity and contested data of science-in-the-making, needs to be addressed in science education to tackle RRIs and to support decision-making abilities. Science education must acknowledge the uncertain nature of RRIs and engage with this dimension of scientific research.

Besides uncertainty, the teaching of RRIs in science classes needs to convey an understanding of science in its social context and to illuminate the powers and limitations of

[20] Compare Howes (1975), Layton (1993), DeBoer (2000), Ryder (2001), Aikenhead (2006), Roberts (2007), and Allchin (2014).

scientific processes (Christensen 2009). Scientific research does not occur in a vacuum, but it is a practice, like many others, that is embedded in various contexts.[21] The assessment of risks does require contextualised scientific knowledge if students are to be able to understand the scientific origin and consequences of risk. In addition, knowledge of the nature of science is equally important for risk assessment and management. This enables students to appreciate the impact of risks in a wider social and societal setting to evaluate different experts' opinions and to recognise stakeholder interests, which might influence the direction of scientific research and the presentation of research data (Cross 1993; Ravetz 1997).

Traditionally, science is presented as value-free,[22] but in reality, the direction of research can be influenced by stakeholders who pursue their own interests by promoting certain directions of research. An example of this is the existence of a subset of infectious diseases called neglected tropical diseases (NTDs). This biologically diverse group of diseases shares neither a specific group of pathogens nor certain strategies for treatment. Instead, the term originated from a socially constructed dilemma. These diseases predominantly appear in the tropics and mainly affect people living in poverty. This constellation appears to offer little incentive for funders, researchers, and policy-makers to invest time and money in combatting these diseases. In the case of NTDs, research has been directed (away) by stakeholder's interests. Furthermore, scientists are not free of their own personal belief systems and make assumptions as well as value judgements on a regular basis (Christensen 2009). Science is a powerful tool for explaining and resolving some—but not all—aspects of RRIs. Science must be recognised as a social practice, and its findings must be expanded and understood within their socio-cultural value systems.

Both aspects, uncertainty and science in society, are essential for assessing risks in science classes (for a short summary, see Fig. 6).

4 Risk in the Science Classroom

A central aim of teaching scientific literacy is to enable young people to participate in society as scientifically informed citizens who are able to contribute to democratic discourses and decision-making processes (Laugksch 2000). The ability to address risk is part of the concept of scientific literacy (Levinson et al. 2012) and is characterised by substantial personal and societal significance for the current and future lives of students.[23] Implementing risk and risk assessment education in school curricula is the next step towards helping young people gain the knowledge that will allow them to recognise and respond effectively to RRIs. Undoubtedly, including the topic of risk in science classes involves significant challenges for policy-makers as well as teachers. This section

[21] See Ryder (2001), Aikenhead (2006), Colucci-Gray et al. (2006), Millar (2006), Roberts (2007), and Sadler and Zeidler (2009).

[22] Over time, this traditional approach has attracted its critics. The presentation of science in the classroom has evolved, while Nature of Science (NOS) has emerged as a large field of research in science education. An overview of the history of NOS in science education research, as well as the introduction of a new framework (incorporating more aspects than the traditional approach) in which science can be understood, can be found in Erduran and Dagher (2014).

[23] Compare with Howes (1975), Eijkelhof (1986), Cross (1993), Ravetz (1997), Kolstø (2006), Christensen (2009), and Gigerenzer and Martignon (2015).

Uncertainty	Science in society and science as social practice
– Uncertainty of frontier-science: contested research results, questionable reliability of data, and differing expert opinions – Uncertainty of complexity: multiple factors are involved in risk problems; all might not be known, and their exact influence is often unknown.	– Limitations and power of scientific research – Stakeholder interests and their effect on the direction of research – Scientists' belief systems and value judgements

Fig. 6 Essential elements of understanding and assessing risks (part 2)

aims to discuss possibilities for including RRIs in science classes, considering the previously introduced paradigms of risk and their inherently different concepts of risk.

4.1 Components of Teaching Risk-Related Issues

RRIs are often highly complex topics that contain a range of interrelated variables. Many of these variables are accompanied by aspects of uncertainty, stemming from their complex nature or the contestability of frontier science. Experiencing these complex issues in a protected school setting enables students to acquire and practise the abilities necessary for coping with RRIs in the real world. This, in turn, furthers the citizenship-focused aims of scientific literacy and education (Christensen 2009). Several authors propose to integrate RRIs into science classes.[24]

As shown in this article, the realist and the constructivist paradigms of risk highlight different perspectives on the concept of risk, the formation of risk perception within the human mind, and the functional assessment of risks. Both paradigms of risk must be considered when teaching RRIs in science classes. The following three core components are integral for supporting students in developing the abilities necessary to cope with RRIs. Component (1) represents a synthesis of the realist paradigm's definitions, methods, and concepts of risk. Component (2) uses the understanding of risk within the constructivist paradigm. A conclusive assessment of an RRI, which combines knowledge from both previous components, can be found in component (3).

Thus, teaching RRIs should include the following RRI core components:

(1) Scientific knowledge and statistics/probability

  a. Knowledge concerning the RRI
  b. (Basic) understanding of statistics/probability to be able to comprehend results of experts' risk analysis
  c. Judgement about the reliability of data

(2a) Knowledge about science (uncertainty)

a. Uncertainty of frontier science: contested research results, questionable reliability of data, and differing expert opinions

[24] See Howes (1975), Eijkelhof (1986), Kolstø (2006), and Levinson et al. (2012).

b. Uncertainty in complexity: multiple factors are involved in a risk problem, all of which might not be known, and their exact influence is unclear or unknown

(2b) Knowledge about science (science in society and science as social practice)

a. Limitations and power of scientific research
b. Stakeholders' interests and their effect on the direction of research
c. Scientists' belief systems and value judgements

(3) Risk assessment

  a. Identification and evaluation of risks (and benefits)
  b. Identification and evaluation of alternative outcomes
  c. Completion of a risk-benefit analysis (including scientific/expert, cost, value, and ethical judgements)
  d. Argumentation
  e. Decision-making.

Component (1) is derived from the concept of risk within the realist paradigm and can be divided into three aspects: 'scientific knowledge', 'understanding of statistics/probability', and 'judgement about the reliability of data'. Scientific knowledge is the knowledge that enables students to understand the scientific aspect of the RRI in question. This comprises results and facts gathered from scientific research processes as they are used and encouraged within the realist paradigm. These processes can be seen as part of the realist paradigm insofar as realist methods of measuring risk are applied and allow insights into RRIs. 'Basic understanding of statistics/probability' is a necessary tool to understand many, if not all, results of realist methods, and such knowledge is essential for understanding scientific results, experts' opinions, and information on risk as they are often presented in the media. The last aspect of this component, 'judgement about the reliability of data', integrates an understanding of both the way that science is portrayed in the media and the way it is interpreted by the receiver. Thus, aspects of media competence are part of risk assessment. This includes the abilities to recognise trustworthy sources within media coverage as well as to identify and address attempts at media influence. This aspect can be seen as a bridge to the following core component, as it encourages students to take a step back and consider the research process from an outside position.[25] In sum, component (1) represents the abilities necessary for understanding and working with scientific procedures and results.

Component (2) follows from the broader understanding of risk within the constructivist paradigm and is subdivided into the two aspects of 'uncertainty' and 'science in society'. Both aspects address knowledge about science—that is, the 'role of science in society and science as social practice', as well as the 'uncertainty of scientific research', which stems from conflicting research results and experts' opinions as well as from complexity. This component focuses on promoting students' ability to place the results of core component (1) in a wider social and

[25] For a more in-depth look at media competence concerning RRIs, as well as at ways in which media influence risk communication, consult Hug (2012), Paling (2003), Klebl and Borst (2010), Binder et al. (2015), and Ratcliffe and Grace (2003, pp. 7–9).

cultural setting. RRIs cannot be satisfactorily understood and assessed without placing them in their socio-cultural contexts.

Component (3) focuses on the application of the two paradigms, presented in the previous components, by describing the processes of risk assessment performed by students. These processes start with the identification and evaluation of the risks and benefits associated with the issue being discussed, and they are closely followed by the identification and evaluation of different outcomes as positive or negative. Both of these aspects rely heavily on how information on the RRI in question has been previously evaluated by using components (1) and (2). That is, processing these first two aspects leads to an understanding of the RRI in relation to the state of scientific facts (i.e. 'What does science know about the issue?', including statistical facts) and the limitations and role of the scientific process (i.e. 'What do we know about the science/scientists involved in the issue?').

The next aspect, 'completion of a risk-benefit analysis', is crucial because it represents the final decision-making process. The previously identified and evaluated risks, benefits, and outcomes are weighted against each other. This assessment further expands on costs (i.e. 'Which outcome is more cost effective?'), and it considers value judgements and ethical judgements of a personal and social nature as well (i.e. 'Who profits from the benefits and who suffers from the risks?'). These processes result in a decision about the RRI in question. The teaching unit can be expanded by adding an argumentative module that allows students to present, justify, and defend their risk-benefit analysis. The final decision-making process can be an individual effort or a class effort in which all students in one class discuss and—if possible—arrive at a shared decision on the RRI in question.

4.2 Risk Competence as Part of Scientific Literacy

Bringing risk into the classroom is challenging because the handling of risk in a real-life setting—from risk perception, identification, evaluation, and assessment to decision-making—is a rather complex process, requiring a wide range of different abilities. The previous paragraph outlined three core components that need to be addressed when introducing RRIs in the classroom, which can be seen as part of what can be called risk competence. By definition, therefore, risk competence is a collective term that encompasses all the abilities a person needs to in order address risk-related issues in a real-world setting.

As mentioned earlier in this article, the ability to assess risks and address them is an essential part of scientific literacy, as it enables students to engage in debates scientifically, technologically, and socio-scientifically. Several authors have proposed frameworks to conceptualise scientific literacy.[26] A concise overview of the different frameworks can be found in Kampa and Koller (2016). One of the most popular frameworks for scientific literacy was suggested by Bybee (1997) and later adopted within the PISA. Within that framework, Bybee introduced different levels of scientific literacy (see Table 1). Bybee's framework will be used as an example to demonstrate the level of scientific literacy necessary to address RRIs.

Teaching RRIs in science classes can be seen as an opportunity to work with all levels of scientific literacy, advancing students' content knowledge as well as their procedural knowledge. Students at the level of nominal or functional scientific literacy could be encouraged to work with simplified RRIs on identifying risks and benefits by focusing on core component

[26] Bybee (1997), Fives et al. (2014), Gott et al. (2006), Gräber and Bolte (1997), Hodson (1992), Osborne and Costello (2004), and Shavelson et al. (2008).

Table 1 Bybee's hierarchical framework of scientific literacy (after Shwartz et al. (2006))

Level of scientific literacy	Description
Scientific illiteracy	Students cannot relate or respond to a reasonable question about science. They do not have the vocabulary, concepts, contexts, or cognitive capacity to identify the question as scientific.
Nominal	Students recognise a concept as related to science, but their level of understanding clearly indicates misconceptions.
Functional	Students can describe a concept correctly, but they have a limited understanding of it.
Conceptual	Students develop some understanding of the major conceptual schemes of a discipline and relate those schemes to their general understanding of science. Procedural abilities and understanding of the processes of scientific inquiry and technological design are also included in this level of literacy.
Multidimensional	This level of scientific literacy incorporates an understanding of science that extends beyond the concepts of scientific disciplines and the procedures of scientific investigation. It includes philosophical, historical, and social dimensions of science and technology. Here, students develop some understanding and appreciation of science and technology regarding its relationship to their daily lives. More specifically, they begin to make connections across scientific disciplines and across science, technology, and the larger issues challenging society.

(1), scientific knowledge, and understanding of statistics/probability. In this way, students would have the opportunity to gain insights into the current state of knowledge within the RRI, experience the scientific research process, and develop scientific ways of thinking. Within core component (1), it would also be possible to focus on students' procedural abilities (e.g. evaluative or communicative abilities), such as dealing with graphs or numbers (statistics and probability) as well as verbalising and evaluating facts.

An example of such a simplified RRI might be the risks of an infection with the malaria pathogen. During such a teaching unit, students would be asked to identify risks related to malaria at a strictly individual level. Their learning process would be accompanied by scientific knowledge about the disease, its pathogen, its transmission path, and the symptoms of the disease. This knowledge could be expanded with statistical information about the probability of infection and mortality rates (in the form of graphs and diagrams, as seen in the example of mammographic screening in Fig. 2). By working with this RRI, students could have the opportunity to expand their level of scientific literacy by becoming acquainted with the research process and scientific thinking (within the realist paradigm of risk). This could be reinforced by students' development of procedural abilities, such as the handling of statistical data.

Increasing the difficulty level of the RRI would pull students away from a strictly scientific and realist standpoint and would expand the teaching unit. At this level, students could consider the impact of the RRI not only at the individual level but also at the societal and cultural levels. This is represented by core component (2), 'knowledge about science'. Students could include social aspects, moral considerations, and value judgements in their risk assessment, which would require them to understand the scientific process and its direction within a particular cultural context. The aim would no longer be to simply identify and describe risks and benefits but to evaluate them effectively, expanding upon societal and cultural aspects as well as strictly scientific aspects; the students could also conduct a risk benefit analysis, come to a decision, and defend that decision in an argumentative setting.

An example of such a RRI might be the risks and benefits of using DDT to combat malaria in African countries. During such a teaching unit, students could be asked to come to an informed decision on the use DDT in populated areas in order to exterminate the malaria propagator, anopheles mosquito. Students could gain scientific and statistical knowledge about the disease itself, as in the simplified RRI. This learning would be accompanied by additional features, such as consideration of the uncertain long-term effects of DDT use in human settlements and on the ecosystem. Other additional features would be moral questions, such as considering the necessity of using a neurotoxin to combat malaria despite the existence of an anti-malaria drug (albeit an expensive one) and the renewed (research) interest in malaria, which has resulted from the migration of the anopheles mosquito into richer European countries. This would create the opportunity to consider the scientific process in its cultural and societal contexts and to analyse the extent to which research directions are influenced by stakeholders and financial pressures. These additional features are part of core component (2), knowledge about science, and they add a societal and cultural discourse to the RRI. The teaching units would lead to students conducting a risk-benefit analysis of their own (core component (3)), thus evaluating and weighing the previously identified risks and benefits, which would ultimately allow students to come to a decision on whether DDT should be used. This decision could be expanded in the argumentative phase of the teaching unit, and mutual agreement could be pursued.

As seen in the previous two examples, malaria and DDT usage, the difficulty level of each teaching unit can be adjusted according to students' level of scientific knowledge by adding more or less of the three core components and their respective aspects. Teachers must be informed about their students' current levels of scientific knowledge in order to adjust their teaching unit and work sheets accordingly. Theoretically, by covering all three core components, students should be able to develop their risk competence to include all four of Bybee's (1997) suggested levels of scientific literacy.

4.3 Towards Teaching Risk-Related Issues in the Science Classroom

The different methods of measuring risk and risk perception can serve to support the introduction of RRIs into the science classroom. As discussed in previous sections, there is a distinctive difference between the methods of the realist paradigm and those of the constructivist paradigm, as each one is based on different concepts of risk.

The realist methods are used within the STEM sciences mainly to identify and measure risks by averaging (negative) events over space, time, and context (Singleton et al. 2009). Whilst there are differences in methodology, the approaches of the realist paradigm all exclusively seek to quantify risk based on the risk formula, which can also be modified for specific cases (see Fig. 1). Thus, applying realist methods and dealing with their results can be seen as part of core component (1). In science classes, students can work with research results (i.e. direct results of the application of realist methods), such as scientific knowledge gained from the realist risk assessment process as well as graphs and statistical data, to identify and evaluate risks and benefits. By further expanding on students' procedural abilities, it is possible to conduct simplified experimental setups and calculations based on realist methods.

An example of the application of realist methods in a science class might be an analysis of irrigation in agriculture and the resulting risks of the salinisation of the ground. Students can approach this topic by conducting an experiment that draws on (realist) toxicological methods. In a simple setup for such an experiment, students would cultivate a number of plants, of the same variety and size, under the same conditions (sun exposure, soil), and supply them with standard drinking water and water with varying salt concentrations. During the experiment, students would record plant growth and health over time and identify changes between plants with and without salt water. In this experiment, grounded in the realist paradigm, students would measure the risk of increasing salinisation of soil on plants by recording physical harm—stunted plant growth and death in plants—over time.

Whilst the usage of the results of realist methods and the application of realist methods promote students' procedural abilities as well as their general level of scientific literacy, those practices do not enable them to broach core component (2), knowledge about science. Thus, students can only approach a RRI from within component (1). Consequently, they are not able to master all aspects of core component (3) because they have yet to discuss, for example, the limitations of scientific processes. In the example of agricultural irrigation and salinisation, societal and cultural pressures—as well as ethical and value judgements—have to be taken into account. A final and fully informed decision would thus be rendered impossible, as not all aspects of core component (3) could be answered.

Core component (2) can be included in the risk assessment process by considering methods from the constructivist paradigm. The constructivist paradigm expands the concept of risk by taking the subjective perspective on risk into consideration (Singleton et al. 2009). The psychometric paradigm is one constructivist method that offers a multilayered concept of risk, including many risk characteristics that heavily influence people's risk perception. This method allows for expanding the realist's definition of a negative outcome of risk (i.e. physical harm, which, in the example above, is plant growth inhibition/plant death). Some of the risk characteristics that the psychometric paradigm has identified as having a major impact on the formation of risk perception are, for example, the perceived availability of information on the RRI, feeling of dread, subjective loss of control, ethical values, voluntariness of risk, and personal probability of contact with the RRI (Fischhoff et al. 1978; Siegrist et al. 2007). Students need to consider and discuss these risk characteristics in the science classroom when addressing RRIs. Another constructivist approach, focusing on the economics of risk, could be adopted by students in a simplified form.[27] The economics of risk would allow for a (simplified) decision-making process by considering the degree of satisfaction or dissatisfaction attributed to different outcomes within the RRI. This would include, for example, the satisfaction of farmers, residents, and consumers.

In the example of the RRI of irrigation in agriculture, students would be trained to account for additional societal, cultural, and economic aspects of the issue, such as the interests of a growing population and its demand for more food (which can be addressed by cultivating desert regions through irrigation) and the ethical commitment to protect and preserve nature. In class, this would create the opportunity to discuss differing experts' opinions on the advantages and disadvantages of irrigation and, accordingly, stakeholders' interests within the research process as well as societal and cultural interests. This inclusion of core component (2) in the risk assessment process would let students approach core component (3) in a more comprehensive manner, thus allowing for an informed decision on the RRI in question.

In sum, understanding risk can be considered as an integral part of scientific literacy. RRIs are an aspect of science and technology that permeate research, media coverage, public discourse, and democratic decision-making as well as many aspects of the personal lives of students. Three core components should be used to address RRIs in class (see p. 13). The difficulty level can be adjusted through the choice of the RRI as well as the number of core components involved in the students' learning process. To support students in developing their ability to handle risks, it is

[27] An example of a teaching unit on risk and benefit balancing based around the RRI 'vaccination' can be found in Ratcliffe and Grace (2003, pp. 12–17).

necessary to cover all three core components and therefore work with both the realists' and the constructivists' understandings of risk. Whilst the levels of difficulty of the three core components differ, they should all be introduced early in science curriculum. Core component (1) appears to offer the easiest access to the subject matter of RRIs, and students can, subsequently, quickly advance when core component (2) is introduced. Thus, including the study of risk in science education can be seen as a chance to expand not only scientific literacy but also students' ability to manage risks in a real-life context.

5 Conclusions and Future Research Perspectives

Science education researchers have long argued that risk should be included in the science curriculum.[28] Several features of RRIs are challenging to teach in science classes, but at the same time, dealing with RRIs has the potential to help students not only develop specific scientific knowledge but also deepen their argumentation and decision-making skills, thus supporting their development as scientifically literate citizens who are able to contribute to democratic discourse and decision-making processes.[29]

Addressing RRIs in science classes is important for teaching scientific literacy and for preparing students to address real-world problems. As Beck (1992, p. 20) has argued, "sooner or later in the continuity of modernisation, the social positions and conflicts of a 'wealth-distributing' society begin to be joined by those of a 'risk-distributing' society". An avoidance of risks in one's life is impossible and at times undesirable, as many new technologies bring not only risks but benefits as well. The ability to address risks, stemming from new scientific developments or simply from one's life decisions, seems more and more relevant. Therefore, science classes need to promote 'risk competence' amongst young people. Risk competence can be defined as the set of abilities a person needs to address RRIs in a real-world setting. This article introduced three core components that are necessary to teach RRIs in a classroom setting; together, these components could support students' development of risk competence. The core features of risk competence, structured according to the core components, are summarised in Fig. 7.

Future avenues for research on risk in the science classroom could lead in two directions. On the one hand, there is potential for further research on argumentation and decision-making strategies related to RRIs. As part of risk competence and when addressing SSIs, a stronger—and explicit—focus on RRIs is necessary to foster risk competence.[30] As some SSIs are closely related to RRIs, the results of studies pertaining to SSIs can be used to inform the design of teaching units focused on fostering risk competence.

On the other hand, another research perspective is closely related to risk perception studies in psychology and the social sciences. Psychological risk measurement methods within the constructivist paradigm, such as the psychometric paradigm, could be used to gather more information on risk perception and the factors that influence it.[31] Presently, a large number of

[28] Compare with Howes (1975), Eijkelhof (1986), Cross (1993), Ravetz (1997), Kolstø (2006), Christensen (2009), and Levinson et al. (2012).
[29] See Eijkelhof (1986), Laugksch (2000), Levinson et al. (2012), and Kolstø (2006).
[30] As seen in the study on decision-making strategies concerning high-voltage power lines by Kolstø (2006) and the teaching unit on ionising radiation by Eijkelhof (1986).
[31] For studies applying the Psychometric Paradigm, see Fischhoff et al. (1978), Marris et al. (1997), Finucane et al. (2000), Bronfman and Cifuentes (2003), Savadori et al. (2004), Siegrist et al. (2005), and Siegrist et al. (2007).

Students are able to…

- use scientific/biological knowledge
- apply (basic) understanding of statistics/probability
- deal with uncertainty
- recognize science as a social practice
- understand the role of science in society
- identify and evaluate the risks and benefits in risk-related issues
- identify and evaluate alternative outcomes of risk (favorable and acceptable outcomes, unfavorable and unacceptable outcomes)
- conduct a risk-benefit analysis (comparing estimated loss to estimated personal and societal benefits, consideration of who benefits and who experiences harm)
- identify and communicate arguments

Fig. 7 Core features of risk competence

psychological studies focus on risk perception, but students and science teachers are rarely studied.[32] Such studies might help us understand students' risk perception and the variables associated with it. This research focus is both important to understanding people's reactions to risks and pertinent to science education and its aims of helping students to assess risks adequately and make informed decisions about RRIs. Psychometric scaling could help in illuminating the formation and structure of students' risk perception (i.e. 'What factors influence risk perception?', 'Which risks do students recognise?', and 'How do they rate risks?').

Another approach to describing students' understanding of risk comes from the social sciences. A series of studies (Lupton and Tulloch 2002a, b; Tulloch and Lupton 2002) have addressed the risk epistemologies of adult Australian and British citizens. These studies aim to "elicit the participants' understandings and notions of risk" (Lupton and Tulloch 2002a, p. 317) using an interview-based approach. Participants were asked to define risk and name risks that are most threatening to themselves and society. Applying a similar approach to students and science teachers has great potential to further our knowledge of their respective understandings of risk. Developing new teaching units on RRIs can build on, work with, and enhance students' initial definitions of risk. Furthermore, interviews could reveal certain risk sources that students find threatening as well as risk sources that students feel are negligible. This information could be used as a basis for choosing RRIs for teaching units. Essentially, teaching units could either address RRIs that are important to students' lives or direct students' focus to RRIs that they assume to be irrelevant but are, in fact, of high relevance.

[32] On adolescent risk perception, see Benthin et al. (1993), Simonneaux et al. (2013), and Ramji et al. (2015). On teachers' risk perception, see Gardner and Jones (2011).

Compliance with ethical standards

Conflicts of interest No conflict of interest.

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