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Safety for technology and society – theory and perception of risk

Risk – a colorful term! The gambler who hopes to win, the actuary who calculates life expectancy, the entrepreneur who assesses their market opportunities, the family who evaluates the future benefits of a consumer good, the patient who considers the success or failure of an operation, the technician who investigates the possibilities of accidents and mishaps – they all start from a common concept: the concept of risk. But do they always mean the same thing?

In the insurance industry and in the natural sciences, risks are defined as the expected extent of damage per unit of time, i.e., risks are determined by specifying empirical values as to how many people on average suffer damage per year or decade. In the humanities, risk is understood as the epitome of the unforeseeable consequences of an event or action, or even as the sum of the threats to our lives and our environment. In addition to the exact scientific definition and the more philosophical approach, the intuitive view of risk is of course also of interest: what do people consider to be risky, how do they assess risks and how do they cope with risky situations? Exploring the tensions between scientific and intuitive risk perception and developing political recommendations for decision-makers from this comparison is a key task of interdisciplinary research.

Scientific risk analysis attempts to use mathematical methods to introduce systematic regularity into the wide range of possible event sequences. But how can events that may or may not occur in the future be brought into a regularity? Can science provide an answer as to whether you win or lose at roulette?

If that were the case, all risk researchers would be millionaires. Unfortunately, they are not! Because the winning numbers in the lottery, the sequence of numbers in roulette, or the outcome of a raffle can no more be predicted than the occurrence of a single accident in a nuclear power plant. What science can do is to indicate the probability of someone winning the lottery or of an accident occurring in a nuclear power plant.

The concept of probability is intuitively difficult to understand. A typical example is the toss of a coin. Even the knowledge that heads or tails each occur with a probability of 50 % (1 : 1) does not improve the chances of winning in the slightest; it may well happen that the coin falls on heads ten times in a row.

However, if a player and a teammate perform many thousands of tosses in a row, you can be almost certain that the player and teammate will have about as much money left after the game as they originally bet, i.e., everyone has lost as often as they have won. This is the statistical law of “large numbers.” The more cases you consider (number of coin tosses), the more likely it is that the calculable probability distribution of events (50 % heads, 50 % tails) will be reached.

However, the coin toss is about probabilities that experience has shown to occur repeatedly within a certain number of cases or within a limited period of time, such as lottery wins, fires or traffic accidents. A whole series of events are so rare that they cannot be estimated by experiment or experience. For example, the probability that the coin will stop exactly on the edge when it is tossed. Even if this special case occurs once in a game with 50 rounds, it is not possible to derive a regularity from it, and it is not possible to draw conclusions about the probability of how often this event can be expected per toss. Only if you toss coins for years, and the rare event occurs more often, can the chance be determined when, on average, an upright coin can be expected.

The statement that an event occurs once every ten thousand throws, or, in the case of continuously acting risk sources, once in ten thousand years, therefore says nothing other than that the frequencies of the rare events are collected in relation to the normal events and used to form an average value with the specification of a confidence interval. A probability of occurrence of once in a million years gives no indication of the exact time of the event, nor can one be certain that this event really occurs once in a million years. All we know is that on average there is a single possibility that the event will occur in a given year, but 999,999 possibilities that it will not occure.

In the absence of sufficient empirical values for the occurrence of rare events, it is not possible to specify a probability in purely statistical terms. Instead, simulation models are used in such cases. Here, the probabilities of rare events are determined indirectly through experimental studies, by transferring empirical values from related areas and through system-analytical models. Such simulated procedures are particularly important today, as the development of modern technology is often accompanied by an increase in the potential for damage, in the technical language of risk theory, and the “hazard potential” increases. The greater the “hazard potential,” the less acceptable it is to use “trial and error,” i.e., through operation and accidents, or to gather empirical values about the probability of damage over a long period of time. Instead, the possibilities and dangers of the relevant risk sources must be assessed in a forward-looking analysis, and the extent of the risk must be clarified in advance.

1. Methods and results of forward-looking risk calculations

With today's technology, a forward-looking risk analysis is therefore necessary. But how can incident sequences be investigated in advance, their probability of occurrence determined, and the extent of damage associated with these incidents determined?

Incidents arise from a triggering event, a breakdown or operating error, which can never be ruled out. Large-scale facilities – and nuclear power plants in particular – have extensive safety systems in place to limit the effects of such incidents.

In an event sequence diagram – as it is called by the technicians – the chain of individual events is simulated, from the triggering breakdown to all conceivable incident sequences. At each stage of the incident sequence, the respective safety system is asked whether it will successfully fulfill its tasks or whether it will fail. If the system works, then the incident is under control and there are no serious consequences. However, if it fails, then the next stage of the incident progression occurs and damage may be caused. Failure probabilities can be specified for each system switching point or branch in such an event sequence diagram, which are determined using the so-called fault tree analysis. In this type of analysis, a failure is assumed and the possible causes are determined. The causes are traced backwards until individual components are found whose failure rates, i.e., the probability of failure, are either known from experience or can be determined experimentally with reasonable effort. Inaccuracies in the calculations are compensated for by increased safety margins in the probability data. Multiplying the probability of occurrence of the triggering events by the probabilities for the functioning and non-functioning of the respective subsystems in the course of the accident results in the probability for the accident sequence under consideration. As an example, Figure 1 shows the event sequence diagram for a large leak in the main cooling circuit of a nuclear power plant, which can also be used for the design basis accident (maximum credible accident, MCA).

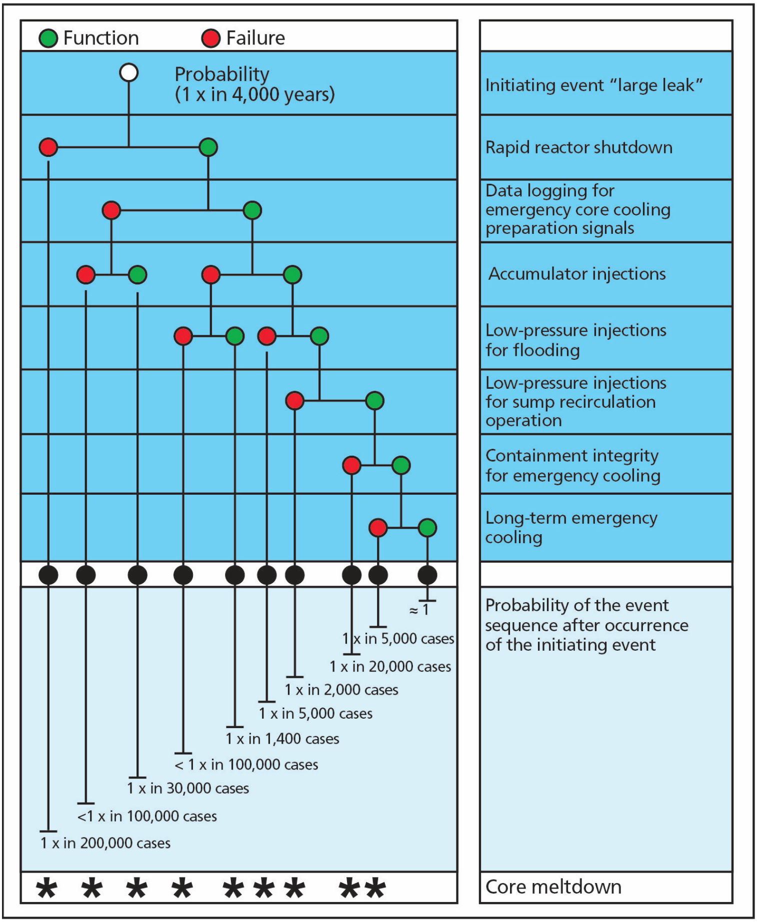

*Figure 1: Event sequence diagram for a "major leak" incident at a nuclear power plant. The probabilities for an assumed event sequence, multiplied by the frequency of the triggering event (2.7 x 10–4 per year), result in the frequency of the individual event sequences. The symbol * indicates whether the event sequence leads to a [reactor; the editors] core meltdown.*[1]

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[1] No sources were cited for any of the images in the original publication.

The probabilities for a given sequence of events can therefore be determined in the manner described. Depending on the course of the incident, there are possible effects on the environment (such as the release of radioactive substances), which lead to specific levels of damage based on known or calculable dispersion models and weather conditions. This includes short-term fatalities, injuries, genetic damage, long-term effects or damage to property. Multiplying the probabilities of a possible incident sequence by the extent of personal injury or property damage gives the risk of harm from a specific incident by definition. Provided that all conceivable accident sequences are examined, the total risk can be determined from the sum of the partial risks.

An example of such a comprehensive risk analysis is the German Risk Study for Nuclear Power Plants in the Federal Republic of Germany (Figure 2). The figure shows the expected probability per year of incidents leading to a certain number of early fatalities for the operation of 25 nuclear power plants. Due to the existing data uncertainties, the curve is provided with relatively large error ranges in which the relevant value is valid with 90 % certainty.

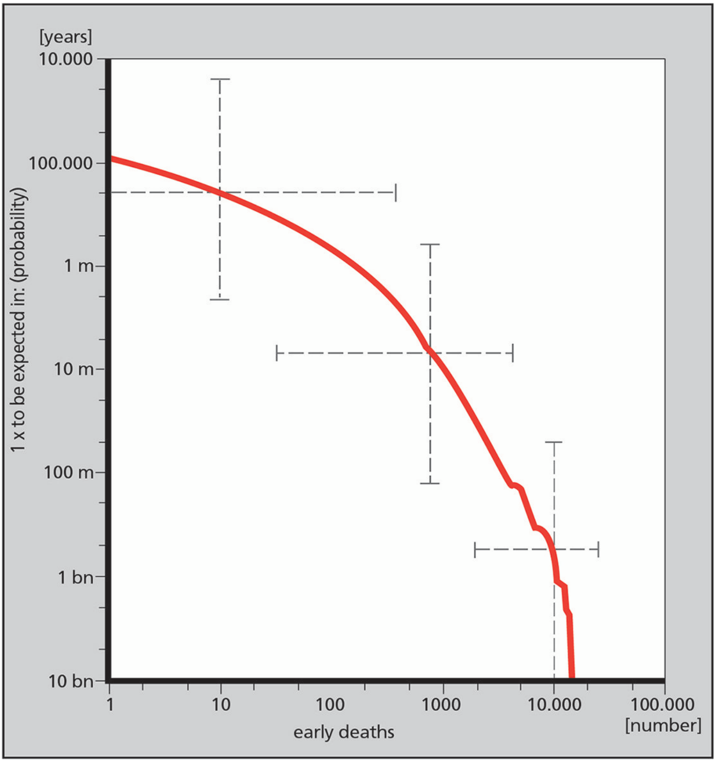

Figure 2: Complementary frequency distribution of early deaths, determined according to the expected values. The error bars indicate the 90 % confidence intervals, i.e., the correct value lies within these intervals with 90 % confidence. The plot applies to 25 nuclear power plants in the Federal Republic of Germany.

A comparison of the risk curve of nuclear power plants with the risk values determined for other technical facilities shows that nuclear power plants pose a relatively low risk to the population. To date, such careful and comprehensive risk studies have almost exclusively been carried out in the field of nuclear technology, risk assessments for large-scale petrochemical plants, such as those on Canvey Island (UK), result in much higher risk values.

Overall, the results of risk analyses show that the dangers associated with the use of nuclear energy are of the same order of magnitude or considerably smaller than those associated with other technical systems that people have known about for a long time. Based on this, one would have to assume that nuclear energy is a perfectly acceptable method of energy generation due to its calculated risk and as such is also acceptable to the population. Since this is obviously not the case, the concept of risk must be understood differently by the population. The understanding of intuitive risk perception can no longer be derived from considerations of the technical concept of risk. Psychological and social science theories and models can help here.

2. The intuitive perception of risks

If citizens assess the risk of nuclear energy differently from risk theorists, who take the scientific definition of risk as their starting point, then there may be three reasons for this:

- People do not know the results of the risk analysis, but make their own intuitive risk assessments,
- People know the results of the risk analysis but do not believe them, preferring instead to trust their intuitive convictions.
- People know the results and also believe the expert assessments, but they do not use this information as decisive criteria for their risk assessment.

Which of the three explanations is correct? Figure 3 provides an answer to this question. This chart shows the results of a survey in the U.S. and the Federal Republic of Germany. Several hundred people were asked to estimate the risks of various sources of danger, from tobacco smoking to nuclear power plants, in terms of losses per year. The estimated values are plotted on the y-axis, the actual statistical figures are shown on the x-axis. As can be seen at first glance, the estimated values for losses and the statistically determined "true values" are relatively close. However, the general trend for both the U.S. and the Federal Republic of Germany is that very high-loss risks are slightly underestimated, and very low-loss risks are slightly overestimated, meaning that people's perception of the extreme values is more in line with the midfield. Nevertheless, the correlation between the estimated and actual values is surprisingly good. Accordingly, thesis 1, according to which people are simply misguided in their estimates, cannot be correct. Since the trustworthiness of scientific risk analyses is hardly ever questioned in surveys, thesis 2 cannot be true either. This leaves only the third explanation.

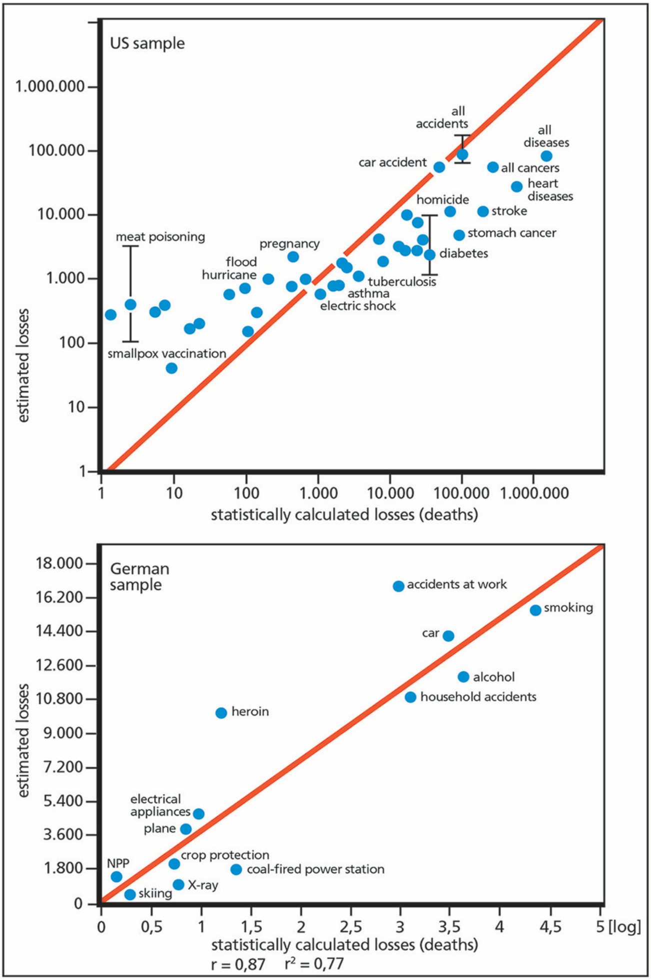

Figure 3: The population's estimate of the level of loss rates for various sources of risk compared with the statistically calculated values. The upper graph shows the results of a U.S. survey, the lower graph the results of a German survey. It can be clearly concluded from both surveys that intuitive loss estimates (here expected deaths per year) are relatively close to the true statistical values, but that very high-loss risks are underestimated and very low-loss risks are overestimated.

3. Imagined complaints – a guide to the psychology of risk perception

Before the question of the type and quality of the loss-independent risk assessment is addressed, a further survey result must be described, which was again implemented graphically (Figure 4). The mean values of the risk assessment of three independent samples from several areas of the Federal Republic of Germany are plotted in a coordinate system. There are only 100 or 500 interviewees in each case, so one would expect a wide spread of results, however, the risk estimates for all three groups are almost identical (the closer the points are to the diagonal line, the more similar the results). This is astonishing, especially as the dispersion within the individual groups is also low, i.e., most people answer in an almost identical way when assessing risks. Obviously, there are evaluation criteria that lead to a similar form of risk assessment for most citizens. It has already been explained that this homogeneous response behavior cannot be attributed to the perceived or real average loss rate. This makes it all the more urgent to ask which factors of intuitive risk assessment can give rise to such a similar view of risk.

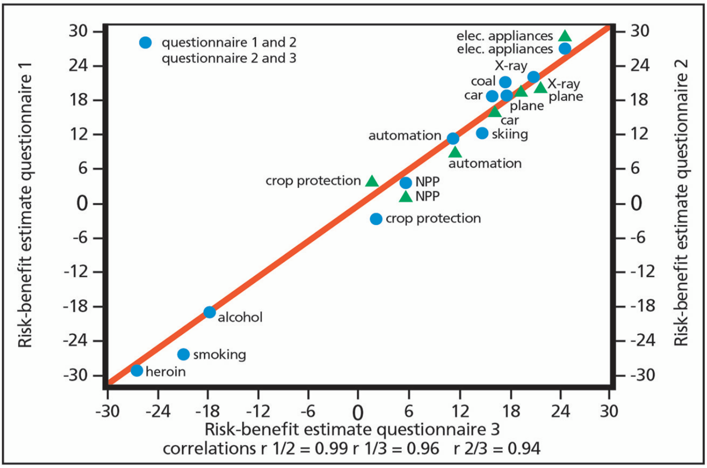

Figure 4: The assessment of various sources of risk according to the degree of their risk-benefit ratio. Three groups of people were given the task of estimating the net benefit of risk sources using a scale from -3 to +3. The surprising result of these surveys was an almost homogeneous response behavior among all three groups of people. This means that people assess risks in a similar way.

To gain an insight into how risks are perceived, a small socio-psychological experiment conducted at the Jülich nuclear research facility is described below. Two randomly selected groups of test subjects were asked by the experimenter to take part in a pharmaceutical trial test. Ostensibly, the aim was to test three different capsule coatings for possible unpleasant side effects. The test director explained to the test subjects that the first capsule contained a radioactive coating, the second a bacterial coating and the third an acid coating, with all three capsules dissolving more quickly in the stomach than conventional materials. There was in fact no health risk with any of the three capsules. In reality, the capsules were three identical commercially available vitamin tablets. The first test group was allowed to make a free choice from three options, the second test group was assigned one capsule each by the experimenter. After taking the capsule, the test subjects completed a questionnaire in which they were asked to provide information about any symptoms (stomach pressure, discomfort, etc.).

The result of this experiment is shown in Figure 5. Although all test subjects had swallowed an identical harmless capsule, the test subjects in the second group, who had not been allowed to make a choice, stated on average twice as often that they felt unwell than those who had been allowed to choose a capsule. This result was completely independent of which capsule coating was chosen or imposed. An interesting side note is that the supposedly radioactive capsule caused the most discomfort in both groups.

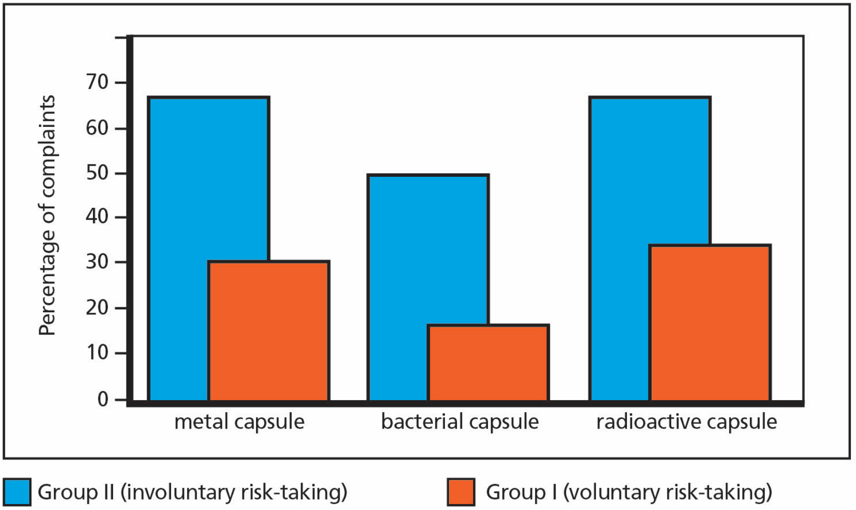

Figure 5: The results of the capsule experiment. Two test groups were given identical vitamin capsules with supposedly different coatings consisting of heavy metal, bacteria or radioactive substances. The members of group I were allowed to choose a capsule, while the members of group II had a capsule allocated by the experimenter. After the experiment, the test subjects were asked about their subjective complaints, such as stomach pressure. This clearly showed that voluntary risk-taking led to significantly lower rates of discomfort.

The fact that voluntariness is a key factor in risk perception has long been an important component of psychological risk and decision theory. However, it was not until this capsule experiment that empirical proof of this relationship was provided. Chauncey Starr has emphasized the importance of these variables in a completely different way. A comparison of statistical loss rates of different sources of risk showed that socially accepted risks taken voluntarily have a 1000-fold higher loss rate than risks that are considered involuntary.

Voluntariness is just one example of a whole chain of loss-independent variables that are referred to as “qualitative risk or benefit characteristics.” Other characteristics of this type are: “personal control possible,” “extreme consequences conceivable,” “danger not perceptible to the senses,” and “accustomed to source of danger.” Surveys can be used to estimate roughly how important these characteristics are for the perception and evaluation of the source of risk. Figure 6 shows the extent to which individual qualitative characteristics are involved in explaining the risk assessment. The y-axis shows the respective correlation coefficient, i.e., the strength of the correlation, while the x-axis shows the boxes with the individual characteristic classes for nine different sources of risk.

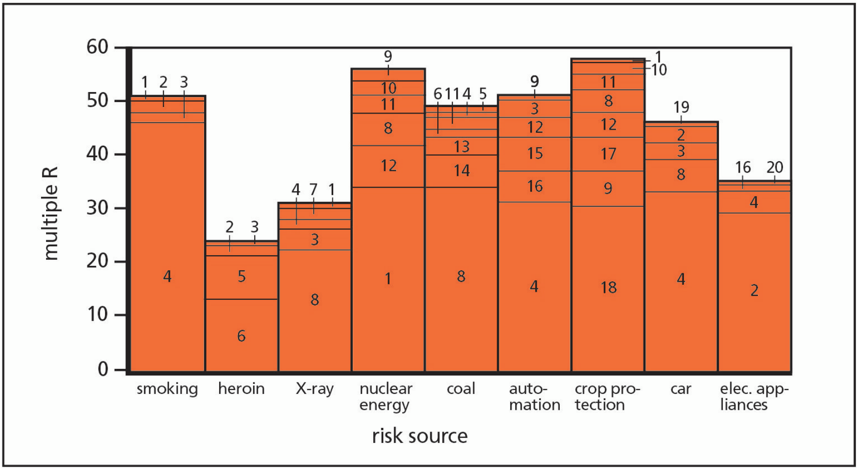

Figure 6: The influence of so-called "qualitative risk or benefit characteristics" on the level of the risk-benefit estimate. The individual bars show the multiple correlation coefficient, i.e., the strength of the correlation between the respective characteristics and the risk-benefit estimate. For most risk sources, benefit-related characteristics play the most important role, but for nuclear energy, crop protection and electrical appliances, risk-related characteristics play the most important role.

1 Catastrophic consequences, 2 Voluntary risk-taking, 3 Personal control possible, 4 Personal benefit/harm, 5 Effects known, 6 Benefit-equivalent alternatives available, 7 Everyday risk, 8 Benefit for all, 9 Safety monitored, 10 Imperceptible risk, 11 Personal control not possible, 12 Unusual risk, 13 Risk imposed, 14 Short-term harm, 15 Unknown risk, 16 Minor consequences, 17 No benefit-equivalent alternatives, 18 Long-term harm, 19 Safety monitored, 20 Scientifically researched.

If we first consider only the primary explanatory factors, i.e., the characteristics that have the greatest influence on risk assessment, it is clear that benefit-related aspects are far more important. People initially evaluate risks according to the possibilities and circumstances surrounding their use, such as whether they themselves can benefit from them, whether the benefit is for everyone or just a minority, and whether there are other alternatives that provide the same benefit with less risk. In the case of nuclear energy, crop protection and electrical appliances, on the other hand, the focus is on the risk characteristics. While the voluntary nature of the use of electrical appliances means that the associated risk is positively weighted, the dominance of the factor "catastrophic consequences possible" in the case of nuclear energy, and "long-term potential for damage" in the case of crop protection has a negative impact on risk perception. This clearly shows that the statistical loss rates are not the decisive motives for skepticism toward nuclear energy and crop protection.

Four risk characteristics that were included in the German survey described above are also recorded in the U.S. The German and U.S. values are shown in Figure 7 for comparison. As can be clearly seen, similar to the intuitive risk assessment, there is a similarity in the response behavior of German and U.S. respondents. With the exception of the ratings for car driving and X-ray diagnostics, the mean values for both countries lie within a narrow band of ± 1 around the diagonal (here the bisector = theoretical uniform distribution). This surprising agreement strengthens the assumption that qualitative risk characteristics are to be regarded as psychological weighting criteria that claim universal validity.

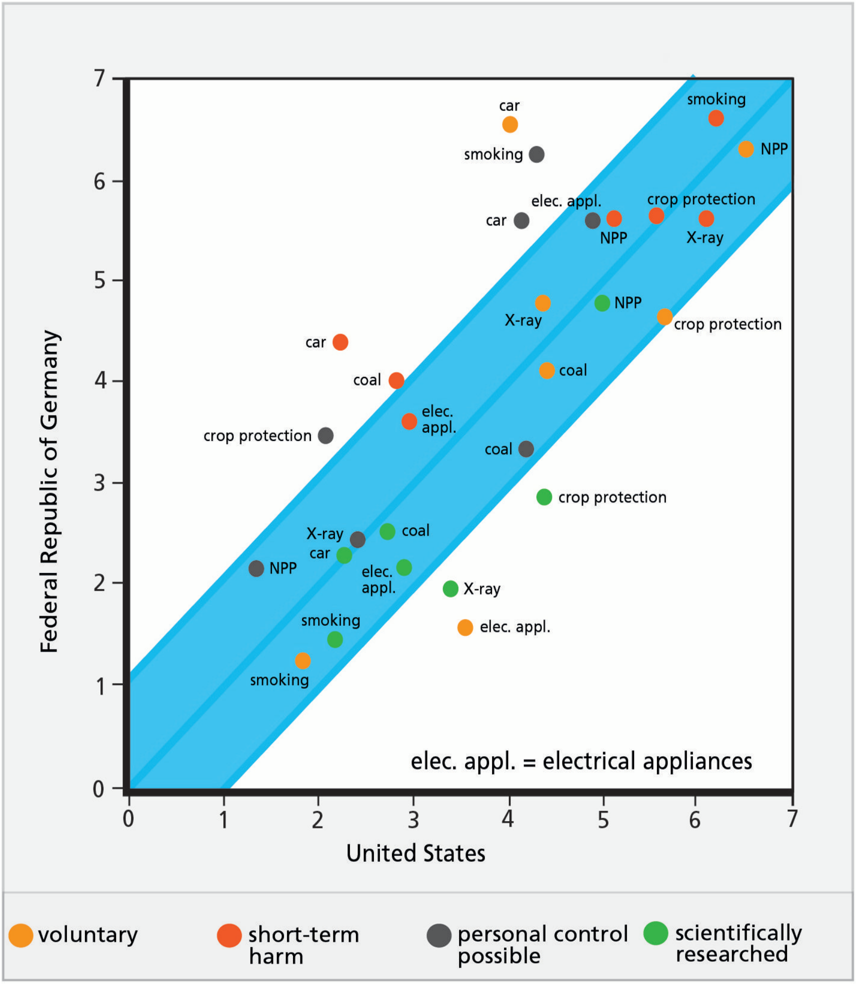

Figure 7: A comparison of the assessments of qualitative risk characteristics between a German and a U.S. survey. Respondents were asked to mark on a scale from 0 to 7 the extent to which the respective qualitative characteristic is typical for the sources of risk examined. This task also showed a clear correlation between the estimated values of the German and U.S. samples.

However, this should not lead to the conclusion that the qualitative characteristics are the decisive factors for risk assessment. The level of the correlation coefficients (Figure 6), which reflect the strength of the relationship between two variables, shows that the risk and benefit characteristics, like the loss expectations, only partially influence the perception of risk.

4. Risk sources more important than risk size

Expected loss rates and qualitative risk or benefit characteristics are two important categories by which people judge risks. However, the capsule experiment already made it clear that not only the abstract risk information (test subjects were told the risk was the same for all capsules) is seen as a decision criterion, but even more so the ideas and opinions relating to the source of the risk. Thus, the "radioactive" capsule triggered the most negative associations and accordingly caused the most frequent "imaginary" complaints. When perceiving risks, people do not separate the extent of the risk from the object from which the risk emanates. The observer is not indifferent to whether the identical risk emanates from a nuclear power plant or from a ski slope: on the contrary, the risk is only vividly thought through in its assessment when the individual can establish a connection with their ideas and opinions about the object from which the risk emanates.

It is very problematic for empirical research to measure people's perceptions of each risk source and to identify typical patterns of perception. Elaborate experiments conducted by the Risk Assessment Group of the International Atomic Energy Agency (IAEA) in Vienna have come to the conclusion that people classify their perceptions according to the criteria of "indirect effects of the risk source" (e.g., damage to health), "economic benefits" (e.g., increase in national income), "environmental risks" (e.g., pollution), "psychological and physical implications" (e.g., environmental impact) and "environmental risks" (e.g., pollution), "psychological and physical implications" (e.g., controllability of risks, artificiality of risk sources), and "impact on social and technical progress" (e.g., security of supply, social balance). These five dimensions of perceptions were obtained on the basis of survey results for the assessment of various energy systems. As this only covers part of the possible sources of risk, an intensive survey of 12 different sources of risk was carried out in a further study by Jülich in order to identify the most important ideas about the consequences of these sources of risk. With the help of a series of statistical procedures, the ideas surveyed were traced back to their central basic patterns (factor analysis) and made comparable by aggregation. The result of this evaluation was a classification and ultimately an evaluation of risk sources according to the following five aspects:

- Effects on the individual and the social environment (health, level of care, safety, etc.).
- Directly affected (personal benefit, harm, comfort, personal well-being, personal freedom, etc.).
- Impact on economic and social welfare (labor market, social balance, general standard of living, quality of life, etc.).
- Socio-political and social values (social justice, democratic rights, equal distribution of benefits and harms, etc.).
- Effects on the conditions for coping with the future (maintaining the level of performance, defending the scope for freedom, securing the level of care, etc.).

Not all of these five criteria apply to all risk sources, and the importance of the individual factors also varies considerably. To provide an overview of the strength and composition of the five criteria for different risk sources, the total values of the individual factors for six risk sources have been summarized in Figure 8. The bars below the zero line show negative assessments with regard to the risk source in question, while the bars above the zero line show the corresponding positive assessments.

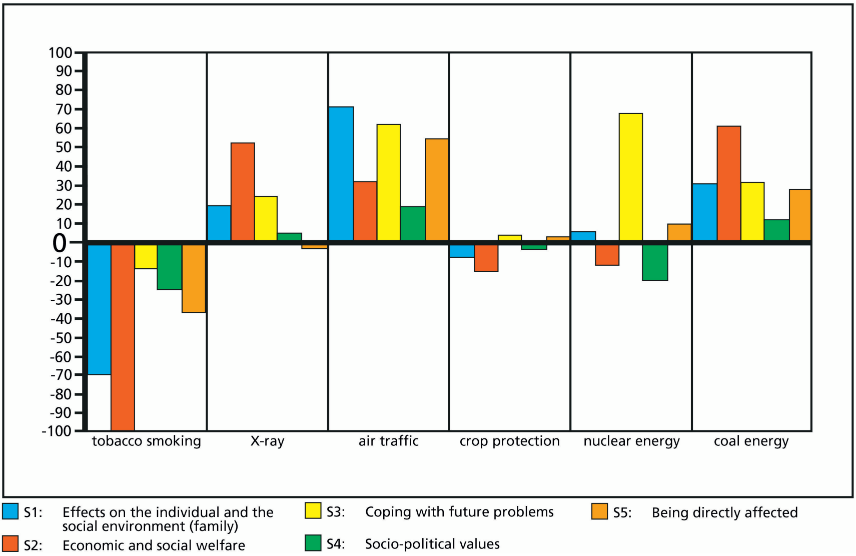

Figure 8: The importance of perceptions and associations about the risk source for assessment of the overall risk. For each risk source, the bars show the extent to which the five factors, which collectively cover the spectrum of the perception system, are used as essential assessment criteria for intuitive risk perception. The ambivalent assessment of nuclear energy and crop protection can be seen particularly vividly in the image.

A comparison of the bar charts for coal and nuclear energy clearly shows why nuclear energy suffers so much more from acceptance problems than coal energy. On average, the population associates the use of nuclear energy with a negative impact on social welfare and the realization of social values. In contrast, the direct and indirect benefits of nuclear power for their own lifestyle are perceived to a lesser extent. This negative preponderance can only be compensated for by the belief in the future role of nuclear energy in solving outstanding energy problems. The hope in the future necessity of nuclear energy prevents a consistently negative attitude toward nuclear energy. In contrast, only positive responses are found for coal, with the criterion of general welfare achieving the highest numerical value. Acceptance problems are therefore not to be expected with coal as an energy source, at least not for the majority of the population.

The assessment of pesticides is particularly ambivalent. While very negative aspects compete with some positive aspects in the case of nuclear energy, the values for crop protection scatter to a small extent around the zero value. This preference for the zero category is due less to an undecided assessment of the risk by the individuals than to extreme differences between individuals, some of whom gave very positive and some very negative gradations. The mean values around zero thus reflect a strongly polarized field of opinion. This reveals a process of perception of chemical interventions in the food chain that roughly reflects the situation regarding nuclear energy at the beginning of the public controversy in 1974.[2] For those responsible in politics and industry, these studies provide an opportunity to anticipate and avoid an escalation of the controversy and to get the problem of chemical additives in the food cycle under control at an early stage.

As a contrast to the perception profiles described above, Figure 8 also shows the perceptions for cars, tobacco smoking and X-ray diagnostics.

5. Rational versus irrational risk perception – a false starting point

If we take another look at the determinants of intuitive risk perception, three levels of influencing factors emerge that essentially reflect the population's assessment of risks. These are:

- The perceived expectations of loss,
- The qualitative risk and benefit characteristics,
- The ideas and opinions relating to the source of risk.

Some personality traits, such as a willingness to take risks and related attitudes, for example toward technological progress per se, should also be added, which will not be discussed further in this context. The level of intuitive risk assessment, which leads to relatively similar results between individuals and within the various social classes, only emerges from the interplay of these influencing factors. When weighing up risks, people generally perceive the statistically determined loss probabilities quite accurately, even if they lack direct insight into the significance of synthetic probability models. However, the statistically determined

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[2] *Editors' note:* The anti-nuclear movement in Germany dates back to the late 1960s and reached its first peak in the early 1970s, when large demonstrations prevented the construction of a nuclear plant in Wyhl in south-west Germany near the border with France.

measures of risk are not the sole criterion for assessing risk. This is where the scientific definition of risk and its intuitive implementation differ. While experts, for well-considered reasons, limit their risk calculation to the aspects of expected loss per time, laypersons process this information together with considerations of risk-specific circumstances (such as voluntariness) and with ideas about the corresponding source of risk. The layperson's perception is therefore more comprehensive, but less precise.

What can we learn from this juxtaposition? The artificial contrast between a rational expert assessment and an allegedly irrational lay assessment has not only obscured the true situation in today's discussion about risks, but has also made dialogue considerably more difficult. The technical calculation of risk levels is undoubtedly an important part of any decision on sources of risk and at the same time is an ideal tool for constantly improving the safety of the population. This is not at all controversial among the general public! However, making such calculations the sole criterion for the "acceptability" or "desirability" of technologies or other non-natural sources of risk contradicts the intuitive view of risk acceptance and is also unreasonable from a political and social point of view. Rather, it is precisely the accompanying circumstances that must be analyzed, and the consequences for people and society assessed, in order to compare people's fears and ideas about the effects of the observed sources with the real situation, and to correct any undesirable developments, or to avert them with foresight, and ultimately to make comprehensible decisions that reflect all levels of intuitive perception. It will only be possible to initiate a fruitful dialogue between scientists, decision-makers and citizens if we learn to take the structure and characteristics of the general view of risks seriously, and to specifically address and tackle the factors that flow into intuitive perception. If this is not achieved and people talk past each other, then the next acceptance crisis is not far away. Natural scientists, social scientists and politicians are called upon to work together to analyze the risks of modern civilization and to explore them in all their nuances so that humans, technology and nature can continue to live together in harmony.