Understanding and Improving People's Judgments of Synergistic Risks

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Understanding and Improving People's Judgments of Synergistic Risks

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This thesis is the original work of student registration number 21908397. Where material is obtained from published or unpublished works, this has been fully acknowledged by citation in the main text and inclusion in the list of references.

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Declaration of Authorship

This PhD thesis is the result of work conducted wholly or mainly by Ian Dawson whilst in registered candidature. None of the material presented has been submitted for another degree. Minor aspects of the thesis have been developed from work conducted jointly with other persons who have assisted in supervisory or advisory roles. Details of the contributions made by others are outlined below.

Chapter	***Co-Authors and Advisors***	***Contribution***
One	Professor Johnnie E.V. Johnson (Co-Author) School of Management, University of Southampton, UK.	Provided advice on methodology and feedback on drafts of paper
	Dr Michelle A. Luke (Co-Author) School of Management, University of Southampton, UK.	Provided advice on methodology and feedback on drafts of paper
	Dr Raquel Flores-Lopez School of Management, University of Southampton, UK.	Provided advice on statistical analysis of data
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Research Dissemination Status

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Two	Manuscript entitled "*Subjective Judgments of Synergistic Risks: A Cognitive Reasoning Perspective*" submitted to *British Journal of Psychology* (ABS rating: 3*).	Paper accepted for publication
Three	Manuscript entitled "*Developing and Testing a Composed Format to Assess Subjective Risk Judgments for Combined Hazards: Helping to Understand Non-experts' and Domain-experts' Assessments of Synergistic Health Risks*".	To be submitted to Journal of *Behavioral Decision Making* (ABS rating: 3*)
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Four	Manuscript entitled "*Helping Individuals to Understand Synergistic Health Risks: An Assessment of Antecedent and Probabilistic Message Contents*".	To be submitted to *Risk Analysis: An International Journal* (ABS rating: 4*)

Abstract

Certain hazard combinations present a risk that is greater than the sum of the risk attributable to each constituent hazard. These 'synergistic risks' occur in several domains, can vary in magnitude, and often have life-threatening consequences. However, research concerning the extent to which people understand synergistic risks is in its infancy, and extant studies investigating this topic have encountered problems in identifying valid measures of subjective risk judgments for combined hazards. Consequently, few firm conclusions can be made about the extent to which people understand synergistic risks.

This thesis presents four original research papers that aim to provide greater insight into peoples' judgments of synergistic risks, and investigates how such judgments may be assessed and improved. Each of the studies presented in the four papers employs data obtained via questionnaires specifically designed to address each research question. In the first paper, two studies are presented that examine whether people believe that combined hazards can present synergistic risks. In the second paper, qualitative data is analysed to explore the cognitive reasoning that individuals employ when assessing the risk for combined hazards. The third paper presents a study that assess a new metric for the assessment of risk judgments for combined hazards, and a second study in which domain-experts' and non-experts' judgments are compared. The final paper features a study that investigates which message content (i.e., antecedent vs. probabilistic data) most effectively informs people about synergistic risks.

The results show that many people can make veridical judgments of synergistic risks. The findings indicate such judgments may depend on factors that include hazard-specific knowledge, judgmental experience and a rudimentary awareness of an

underlying causal mechanism for the increased risk. However, many people also make non/less veridical judgments; often underestimating the magnitude of the synergistic risk or employing an additive risk model which corresponds to the notion of ‘adding’ one hazard to another. Furthermore, the findings suggest risk judgments for combined hazards do not vary according to hazard domain but, rather, according to the hazard characteristics. Importantly, the research also identifies both (a) a valid method of assessing peoples’ risk judgments for combined hazards, and (b) risk communications contents that can lead to significant improvement in individuals’ understanding of synergistic risks.

Introduction

Preface

This thesis consists of four original research papers that collectively investigate individuals' understanding of synergistic risks and identify potential ways in which this understanding can be improved. Although the four papers are related by this common theme, each paper is written as an independent piece of work that can be read and understood autonomously. Prior to the presentation of the first paper, there is a section below entitled '*Risk Perception and Subjective Judgments of Risk*'. This section provides the reader with an understanding of the main theoretical and empirical contributions to the field of risk perception and also reviews the key literature concerning the cognitive factors that can influence subjective judgments of risk. There is a subsequent section, entitled '*Subjective Judgments of Synergistic Risks*', which provides an overview of the rationale for the present research and explicates the research objectives that are addressed in each of the four papers. Following the fourth paper, there is also a short conclusion chapter which provides an overview of the contributions of the work. In addition, the implications of these findings for policy and future research are discussed.

Risk Perception and Subjective Judgments of Risk

In 1978 a group of US-based researchers conducted two studies that ultimately served as a catalyst for the establishment of 'risk perception' as a single research discipline and, in doing so, formed a new methodological approach to the study of human responses to hazards. In the first study (Lichtenstein, Slovic, Fischhoff, Layman, & Combs,

1978) participants were asked to estimate the frequency of 41 causes of death relative to the provided 'anchor' of the number of annual deaths caused by motor vehicle accidents. The participants' judgments were subsequently compared to national statistics for the mean frequencies of the same 41 causes of death for the years 1968-1973. The findings showed that the participants generally judged the frequency of death by each cause in an order closely matching that of the statistical order. That is, they provided accurate judgments of the frequency of each cause of death relative to the other causes. However, the results also showed that the participants' judgments of the absolute frequency of causes of death were less veridical, with overestimations of the low frequency causes of death and underestimations of the high frequency causes of death. In the second study (Fischhoff, Slovic, Lichtenstein, Read, & Combs, 1978) participants were asked to use quantitative scales to rate a variety of hazards (e.g. smoking, police work, etc.) on a number of predetermined characteristics (e.g. voluntariness of risk, immediacy of effect, etc.). From the mean scale ratings the researchers observed correlations between several characteristics across the group of hazards. Subsequently, the ratings were subjected to factor analysis, which revealed the correlations could be accounted for by two factors composed as follows:

- Factor 1:
    - Controllable/Uncontrollable
    - New/Old
    - Involuntary/Voluntary
    - Poorly known/Well known
    - Delayed consequences/Immediate

- Factor 2:
    - Fatal/Not fatal
    - Dreaded/Common
    - Catastrophic/Chronic

The two factors have been labelled 'unknown' and 'dreaded' respectively (Brun, 1994).

From the empirical evidence gathered in the studies by Lichtenstein *et al*. and Fischhoff *et al*. it became apparent that perceptions of risk could be inherently subjective and partly determined by the perceived characteristics of the target hazard (Berry, 2004). From a methodological perspective the studies also demonstrated the feasibility of using psychometric scaling techniques as a means of gathering data on perceived risk; an approach that would eventually be titled "the psychometric paradigm" (Finkel, 2008; Slovic, 1992). The studies have served as a "blueprint" for numerous other risk perception studies based on similar methodologies. In 1980 Slovic, Fischhoff & Lichtenstein again used factor analysis to account for correlations between their participants' ratings of the characteristics of various hazard. However, this time the researchers used a larger group of participants that were asked to rate 90 different hazards on 18 characteristics. In addition to finding the dimensions of 'dreaded' and 'unknown', a third dimension was revealed regarding the 'frequency and extent of exposure' to the hazardous outcome. Similar subsequent studies conducted in different countries have generally found the emergence of the same two or three dimensions (see Bennett, 1999; Borodzicz, 2005).

Shortcomings in the aforementioned studies by Slovic and his colleagues were identified, and this led to further studies that aimed to overcome the criticisms whilst still using the psychometric approach. For example, Slovic *et al*.'s studies had used unrepresentative populations (i.e. women only) and only analysed mean responses to hazards, thus providing a measure of the average or 'societal' response to risk rather than accounting for individual differences. In response, Gardner and Gould (1989) completed a study of risk perception using a probability sample to examine individual differences in the perceived risk associated with a small number of technological hazards. From these modifications it was revealed that the original model could only accounted for 20% of the variance in perceived risk; a result that has been consistently repeated (Sjoberg, 1996). Similarly, Sjoberg (1993) argued that the previous psychometric studies had used a limited number of response scales that would inevitably lead to the emergence of only a few factors, and that the scales were not designed to account for more contemporary aspects of risk perception (e.g. interfering with nature, ethical concerns, etc.). Subsequently, Sjoberg developed the 'Basic Risk Perception Model' (BRPM) which, like the previous studies, uses psychometric surveys to elicit data for factor and regression analysis (Wahlberg, 2001). Like Garner and Gould's approach, the BRPM uses the individual as the unit of analysis as opposed to mean responses. The BRPM has produced the following explanatory dimensions for variance in risk perception:

- *Attitude*: attitude/affect towards a hazard drives perceptions, rather than the other way round.
- *Risk Sensitivity*: an individual's propensity to provide risk ratings of a similar or consistent magnitude i.e. some people are generally more worried by all hazards, as where others are generally less concerned.

- *Specific Fear*: Specific fearful responses to specific hazards. For example, the perceived risk of mountaineering elicits thoughts of falling, hyperthermia, avalanches, etc.
- *Trust*: An individual's trust in those responsible for the creation, operation and regulation of each hazard.
- *Moral Value*: judgments of whether risks are right, wrong, just and fair (Sjoberg, 2000; Wahlberg, 2001)

Research using the BRPM has revealed that 'attitude', 'risk sensitivity', and 'specific fear' are usually the most important determinants of risk perception, and that the model can account for up to 40% more variance in risk perception than the previous psychometric studies (Marris, Langford, & O'Riordan, 1997; Sjoberg, 1996, 2000; Sjoberg & Drottz-Sjoberg, 1994).

Despite the successes of the psychometric approach to risk perception research, it is important to note that this methodology has, arguably, provided results that are somewhat unremarkable. That is, the studies typically find that people are highly anxious (*dread, specific fear*) about the uncertainty (*unknown*) and inequity (*trust, moral value*) surrounding hazards that are believed to have the potential to kill or harm a large number of people (*number of people exposed*). This appears to be exactly the kind of response to a hazard(s) that one might predict from any species that is predominantly concerned with its survival and well-being.

Although some limitations to the psychometric paradigm have been identified, it would be wrong to conclude that the findings from these studies are of limited value and that the approach is now redundant. To appreciate the holistic (and continuing) contribution this approach has made to risk perception research it is necessary to consider the studies in a broader context. Firstly, the early studies demonstrated that the phenomena of 'risk perception' can be empirical observed, and that psychometric methods provide one feasible approach for its measurement. The approach has also revealed that, not only can differences exist between individuals' perceptions of risk and the formal risk assessments generated by official sources, but that risk perceptions are often affect-laden (Slovic, Peters, Finucane, & MacGregor, 2005), multidimensional (McDaniels, Axelrod, & Slovic, 1995) responses that display complex correlations with specific physical and non-physical characteristics of hazards. The evolution of the psychometric studies has also led to the identification that individual differences in risk perceptions exist and that these differences can be statistically observed. Furthermore, the studies have produced data illustrating a positive correlation between the acceptability of a hazard and its perceived benefits (Fischhoff *et al*., 1978; Slovic *et al*. 1980).

Many of the criticisms aimed at the psychometric approach to risk perception research represent a critique of the positivistic paradigm, rather than a critic of the value this particular approach has added to the search for further knowledge in this field (Breakwell, 2007). Evidence of the continuing relevance of this approach can be found in its application to risk perception research some 30 years after its establishment (for an example see Bronfman, Cifuentes, & Gutierrez, 2008). Arguably, one of the principle advantages of this approach is that it provides a means by which the complex and abstract phenomena of human risk perception can be reduced to a format that is suitable for statistical analysis. The resulting data can then be translated into a non-technical format that has the potential to be utilised in the development and delivery of risk management and communication strategies.

Unfortunately, the risk perception studies that have employed the psychometric paradigm reveal little about the specific psychological processes that are at work when risk perceptions are formed and modified. To better understand this aspect of risk perception it is important to examine the key empirical evidence and theoretical observations that consider the cognitive factors that can influence subjective judgments of risk.

In 1956 Simon (1956) introduced the theory of 'bounded rationality' to account for empirical observations indicating that humans often settle for 'sub-optimal' strategies in conditions of risk and uncertainty (Meehl, 1954). The notion of bounded rationality featured two interrelated components; that the human mind has limited computational capacities, and that these computations could be further influenced by the structure of information in the environment (Simon, 1990). Simon proposed that in order to respond to these limitations the mind employs simplifying heuristics that reduce the complexities of judgmental calculations (Simon, 1957). Simon stated that these heuristics work well provided that they are adapted to the structure of the information in the environment; an assertion that has also made by several other scholars and is supported by empirical evidence (see Gigerenzer, Todd & The ABC Research Group, 1999). Although Simon's notion of bounded rationality and heuristics is not a direct account of human risk perception, it does indicate that both cognitive limitations and the structure of the environment can influence how people process information relevant to risk. Subsequently, when people are presented with complex risk-related data or risky situations characterised by scant or ambiguous information, their ability to accurately judge and responses to the risk could be affected.

As stated, Simon argued that some of the cognitive limitations brought about by bounded rationality can be countered by the use of heuristics. However, the reliability and efficacy of such heuristics was brought into doubt by experimental research conducted by Tversky and Kahneman in 1974. Their findings indicated reliance on particular heuristic processes could lead to systematic and significant errors in subjective probability judgments. Given that probability is a key aspect of risk (Wright & Ayton, 1994), the influence of heuristic processes on judgments of probability clearly has implications for perceptions of risk (Brun, 1994). For example, the 'representativeness' heuristic (where the likelihood that 'A' belongs to group 'B' is judged greater if A resembles B somehow) could cause people to ignore evidence showing two food additives which appear similar in many respects are in fact very different at a microbiological level. This can in turn lead to a subjective assessment that the risk from one additive must be equivalent to the risk from the other (Breakwell, 2007). Tversky and Kahnemans' experiments also identified that the 'availability' heuristic (where the probability of an event can be overestimated or underestimated based on the respective ease or difficultly with which an instance of the event, or very similar events, can be recalled) can influence probability judgments. For example, based on the premise that media coverage typically highlights rare events (i.e. plane crashes) but not the frequency of more common causes of death (i.e. stomach cancer), the availability heuristic could partly explain why research (Lichtenstein *et al*., 1978), has revealed people often overestimate small causes of death and underestimate larger ones (Johnson & Tversky, 1983; Kammen & Hassenzahl, 2001). A further heuristic that can lead to bias in subjective probability judgments is 'adjustment and anchoring' (where valuation or probability judgments are insufficiently adjusted from an initial estimate). In the case of this heuristic, for example, individuals could be presented with data regarding a newly identified increase in the risk of lung cancer from tobacco smoking. However, they may fail to adjust their personal risk judgment sufficiently due to their original estimate's 'anchoring' effect. Thus, Tversky and Kahneman's research indicates that cognitive heuristics may influence risk judgments to deviate from objective risk assessments. This may be of concern where such judgments result in maladaptive behavioural responses to risks and hazards.

The 'heuristics and biases' research by Tversky and Kahneman lead to a wealth of similar studies that were able to identify a range of heuristics and associated biases that could hinder subjective judgments of probability (see Gilovich, Griffin, & Kahneman, 2002; Kahneman, Tversky, & Slovic, 1982). The research predominantly relied on the use of experiments designed to stimulate cognitive decision-making processes under pre-defined and controlled conditions (Borodzicz, 2005). This approach provided the opportunity to manipulate probabilities and outcomes and to control for the unwanted influence of other variables (Brun, 1994). However, this approach to data collection has often attracted several criticisms which consequently bring the validity of some of the research findings into question. For example, it is argued that this approach is not representative of real-life situations that usually feature contextual cues and motivating incentives (Beach, Christensen-Szalanski, & Barnes, 1987). Furthermore, the 'heuristics and biases' evidence has been criticised for not giving consideration to the environmental structure that human cognitions have evolved to exploit, and that only when people are presented with 'ecologically valid' conditions can they employ 'ecologically rational' heuristics. For example, Gigerenzer (1991) and Pinker (1997) argue that many of the observed judgmental errors are a product of questions presented in terms of probabilities (i.e. percentages and/or decimals) rather than frequencies. They have presented empirical evidence showing that bias in judgments of likelihood can be significantly reduced using frequency formats (Cosmides and Tooby, 1996; Gigerenzer, 1991, 1994), even for 'naïve' participants making Bayesian inferences (Gigerenzer & Hoffrage, 1995). Although not all evidence indicates frequency formats help improve judgments of likelihood (see Gilovich *et al*., 2002), what can be deduced from this evidence is that heuristic-guided judgments, as Simon originally posited, can be influenced by the content and structure of information in the environment. Thus, it is appears that the computational limitations of the mind and the interrelated structure of external information can affect probability judgments. Hence, there is an onus upon risk perception researchers to maximise the ecological validity of the judgment tasks that they may use in experimental settings.

In summarising the above literature, it is evident that subjective judgments of risk can be elicited in experimental conditions and, subsequently, analysed using inferential statistical in order to gain valuable insight into individual and societal perceptions of hazards and threats they can pose. The value of such insight becomes evident when it is utilised in the design and development of risk communication and management techniques that aim to help individuals to better understand hazards and the extent of their personal relevance. However, the research evidence also suggests that researchers must take care to ensure the design of their experiments take into account the cognitive functioning of the research participants and, therefore, employ experimental designs which aim to minimise the scope for bias in subjective risk judgments.

Subjective Judgments of Synergistic Risks

The famous Greek philosopher Aristotle (c.384-322 BCE) had a particular interest in understanding how separate objects and parts related and combined to form a larger order in the universe. In his writings on this topic, Aristotle formally introduced the concept of 'synergy' when he used the phrase "*the whole is greater than the sum of the* *parts*" (Corning, 1998, p. 136). Despite the theoretical nature of Aristotle's assertion, contemporary empirical research has identified numerous synergies between a wide variety of agents, whereby the interaction or co-operation of the individual agents produces a combined effect that is greater than the sum of each agent's individual effects. Although many of these synergies have been welcomed for their capacity to increase the performance and efficiency of certain individual agents (e.g., alloy metals that are stronger than the sum of the strength of the constituent metals), there is accumulating scientific evidence of synergies which result in adverse effects for living organisms and their environment. More specifically, several studies have shown that the risk (i.e., the likelihood of an unwanted outcome) attributable to specific hazard combinations can be greater than the risk attributable to each constituent hazard when operating individually. The risk that is attributable to these hazard combinations has become known as a 'synergistic risk' (Hampson et al., 1998).

Table 1 presents a non-exhaustive list of hazard combinations that have been found, in empirical research, to present synergistic risks. The list illustrates that synergistic risks are attributable to a wide range of hazard combinations, some of which are concrete (e.g., drugs) and others which are abstract (e.g., stress), and that the outcomes can often be life threatening for both humans and other living species. The continued accumulation of evidence of synergistic risks has motivated social scientists to conduct studies that explore the extent to which people understand this particular risk concept (e.g., Eiser, Reicher & Podpadec, 1995; French, Sutton, Kinmonth & Marteau, 2006; Hermand, Mullet, Sorum & Tillard, 2000). This research has been undertaken for several important reasons. First, many individuals may be exposed to hazard combinations that present synergistic risks. This raises the concern that, if individuals do not understand the magnitude of the threat posed by synergistic hazard combinations, then their willingness to adopt appropriate precautionary behaviours may be inhibited, as could be their motivation to demand social, economic or political action to address the risks (French et al., 2006). Second, people, such as policy makers, regulators, managers, and medical practitioners (i.e., those responsible for managing risks that may affect other individuals and wider communities), may misallocate valuable time and resources if they fail to appreciate the extent of the threat posed by certain synergistic risks (Berenbaum, 1989; Cogliano, 1997). Third, there is little appreciation of which communication approaches are most efficacious at educating individuals about synergistic risks (Lipkus, 2007). Hence, there is clear value in conducting empirical research to assess the efficacy of different risk communication approaches using pre and post intervention measures of individuals' knowledge and judgments concerning synergistic hazard combinations. Finally, there is considerable scope for developing further and more general epistemological knowledge about the ways in which people make subjective risk assessments for multiple and interrelated hazards, particularly where the interaction of the hazards may result in a non-summative risk magnitude (Hampson et al., 1998).

Table 1. A non-exhaustive list of agent combinations that have been reported to produce synergistic risks

Agent Combination	***Potential Outcome***	***Source(s) of Evidence***
Aspirin + Clopidogrel	Internal Bleeding	Hallas et al., 2006
Alcohol + Driving + Age	Fatal Collision	Brick, 2009; Keall, Frith & Patterson, 2004
Alcohol + High Body Mass Index	Breast Cancer	Gapstur, Potter, Drinkard & Folsom, 1995
Alcohol + Tobacco	Laryngeal Cancer	Flanders & Rothman, 1982; Hinds, Thomas & O'Reilly, 1979; Saracci, 1987; Talamini et al., 2002
	Head Cancers	Hashibe et al., 2009; Herity, 1981
	Liver Cancer	Kuper et al., 2000
	Oesophageal Cancer	Castellsague et al., 1999; Lee et al., 2005; Zambon et al., 2000
Alcohol + Tobacco + Obesity	Liver Cancer	Marrero et al., 2005
Carbamate + Organophosphate Pesticides	Toxic Poisoning	Laetz et al., 2009
Complicated Birth + Maternal Rejection	Violent Crime	Raine, Brennan & Mednick, 1997
Climate Change + Habitat Loss	Species Extinction	Hannah, Midgley, Hughes & Bomhard, 2005
Paracetamol + Warfarin	Internal Bleeding	Bell, 1998; Hylek, Heiman, Skates, Sheehan & Singer, 1998
Stress + Caffeine	Hypertension	Lane & Williams, 1987
Stress + Physical Factors	Breast Cancer	Grossarth-Maticek et al., 2000
Tobacco + Caffeine	Coronary Artery Disease	Vlachopoulos et al., 2004
Tobacco + Neuroticism	Heart Disease	Maru & Eysenck, 2001
Tobacco + Radon	Lung Cancer	Darby et al., 2005; Pershagen et al., 1994; Reif & Heeren, 1999
Tobacco + Oral Contraceptive Pill	Circulatory Disease	Croft & Hannaford, 1989; Rosenberg et al., 1985
Urbanicity + Genes	Schizophrenia	Van Os, Pedersen & Mortensen, 2004

Results from a majority of the studies investigating peoples understanding of synergistic risks have indicated that individuals tend to judge synergistic risks, in contrast to the scientific evidence, as additive (i.e., equal to the sum of the perceived risk attributable to each constituent hazard) or sub-additive (i.e., less than additive) (e.g., French, Gayton, Burton, Thorogood & Matreau, 2002; Hampson, Andrews, Barckley, Lee & Lichtenstein, 2003; Hermand, Mullet & Lavieville, 1997). A partial explanation for these latter findings could be derived from Cumulative Prospect Theory which indicates that individuals do not Although these findings suggest that individuals tend to underestimate the threat posed by synergistic hazard combinations, the authors of several of these studies have questioned the validity of the findings, arguing that the participants' judgments may have been artefacts of the psychometric scales employed (French, Marteau, Sutton & Kinmonth, 2004; French et al. 2006; Hampson et al., 2003). Consequently, few firm conclusions can be made about the extent to which people understand synergistic risks or about the efficacy of different risk communication approaches concerning the risk attributable to combined hazards. It is in response to these limitations of the extant literature that the empirical research presented in this thesis has been undertaken.

In much of the extant literature concerning subjective risk judgments for combined hazards, researchers have assessed whether individuals are aware that specific hazard combinations (e.g., radon and tobacco) present synergistic risks. Implicit in this approach is the notion that individuals have an *a priori* understanding of the synergistic risk concept and, therefore, the research objective has been to identify whether individuals employ this concept when making risk judgments for specific hazard combinations. However, the supposition that people are aware, either explicitly or tacitly, of the synergistic risk concept has not been subject to direct empirical assessment. Hence, the first paper (Chapter One) presented in this thesis addresses the question of whether individuals believe that combined hazards can present synergistic risks. This question is important because, clearly, if an individual does not believe that it is possible that the risk attributable to a hazard combination can be greater than the sum of the risk attributable to each constituent hazard, then that individual will underestimate the risk for synergistic combinations.

A second limitation of the previous research concerning subjective risk judgments for combined hazards is that the participants' risk estimates do not reveal what factors (e.g., hazard-specific knowledge) influenced them to arrive at their particular risk estimate. Hence, the previous studies provide little evidence to indicate why some individuals might employ a particular risk model (e.g., sub-additive) and other individuals may employ a different model (e.g., synergistic) in their risk judgments. Importantly, such evidence could highlight the characteristics inherent in veridical risk judgments (i.e., judgments consistent with scientific evidence) for combined hazards and, subsequently, interventions could be developed that aim to nurture or instil these characteristics in individuals. Similarly, knowledge of the underlying characteristics of non-veridical judgments could be equally useful, as risk communications could be developed that discourage such characteristics in individuals' judgments. Hence, the second paper (Chapter Two) presented in this thesis examines the cognitive reasoning processes that are employed by individuals when making subjective risk assessments for combined hazards.

The identification of valid methods of measuring individuals' risk judgments for combined hazards is crucial for two important reasons: First, such a metric could be employed to facilitate the identification of individuals or populations that are aware/unaware of particular synergistic risks. Second, this would enable valid empirical assessments of the relative effectiveness of risk communications aimed at helping individuals' to understand synergistic risks. Hence, in light of the concerns regarding the validity of the psychometric scales employed in previous studies, the third paper (Chapter Three) introduces and assesses a new method for measuring individuals risk judgments for combined hazards. In addition, the third paper also addresses the question of whether domain-expertise can improve the extent to which an individual's risk judgment for a combined hazard is veridical. This question has not been addressed in previous studies. Importantly, an answer to this question could indicate whether (a) domain expertise can improve the veridicality of risk judgments for combined hazards and, therefore, that non-experts' judgments could also be improved via the acquisition of domain-related knowledge and experience, or (b) domain expertise does not improve the veridicality of these risk judgments and, therefore, individuals may be prone, irrespective of their experiential background, to a particular judgmental bias that prohibits veridical subjective risk assessments for synergistic risks.

The last paper (Chapter Four) presented in this thesis examines the extent to which two different risk communication messages help individuals to understanding that a particular hazard combination presents a synergistic risk. One message conveys details of the antecedent mechanism underling the synergistic risk (i.e., the physical interaction of alcohol and tobacco inside the human body), whilst the other message explains the probabilistic risk (i.e., the statistical likelihood of developing cancer for individuals who consume both alcohol and tobacco) of experiencing a particular adverse outcome for individuals who are regularly exposed to the hazard combination. By assessing the efficacy of each of these message types, relative to a control group, two particular shortcomings in the extant literature are addressed. First, there is an absence of studies that make a relative assessment of more than one approach to the communication of synergistic risks. Second, the efficacy of explaining the antecedent mechanism of a synergistic risk has not yet been subject to empirical assessment. The overriding objective of this last paper was to identify the content of risk communications that could be employed to improve the extent to which individuals understand synergistic risks.

All of the studies presented in this thesis have gathered data via questionnaires featuring a judgment task(s) concerning the risk attributable to certain hazard combinations. Each task was specifically developed to address the above mentioned research objectives. Importantly, several steps were taken in the design the studies/tasks to minimise the likelihood that the task itself would bias the participants' judgments. First, each task was designed to be easily understood and void of ambiguity. This was because it has been argued that subjective risk judgments obtained using similar approaches have been biased by complex or counter-intuitive tasks (Beach, Christensen-Szalanski & Barnes, 1987; Borland, 1997; Windschitl, 2002). Second, in all of the studies presented in this thesis, participants were either offered an incentive (i.e., prize-draw entry) for participating in the study or the length of participation was kept to a maximum of approximately 10 minutes. This was to encourage the participants to remain motivated because research has indicated that apathy or boredom can impede the quality of subjective risk judgments (see Goodwin & Wright, 2004). Third, in each of the tasks that featured numerical data this information was presented to the participants in a frequency format and/or the participants were asked to provide judgments in a frequency format. This is because several studies suggest that many of the well-documented biases in subjective probability judgments have been significantly reduced or eliminated when individuals are asked to complete the same judgment task in a frequency format (it is argued that the way in which individual's process information is naturally adapted to making and revising frequency estimates, rather than making and revising probabilities in formats such as percentages and decimals: see Cosmides & Tooby, 1996; Gigerenzer & Hoffrage, 1995; Hoffrage & Gigerenzer, 1998). Finally, in Chapter Three, real-world decision makers were studied. This was to ensure that the data obtained throughout the thesis was not solely representative of university students who, according to some authors, may be prone to judgmental biases and fallacies due to their inexperience of estimating probabilities in naturalistic contexts (Beach et al., 1987).

In summary, this thesis presents four original research papers that, collectively, aim to help understand and improve individuals' subjective judgments of synergistic risks. Each of the studies presented in the papers feature novel data collection methods that have been design to specifically address the research question(s) that remain unanswered or only partially answered in the extant literature. The results obtained facilitate a better understanding of individuals' subjective judgments of synergistic risks and provide a more detailed insight into the approaches that may be most effective at improving these judgments. Hence, this collection of work makes substantial contributions to an area of research that still remains within its infancy.

Chapter One: Do People Believe Combined Hazards Can Present Synergistic Risks?

Abstract

The risk attributable to some hazard combinations can be greater than the sum of the risk attributable to each constituent hazard. Such 'synergistic risks' occur in several domains, can vary in magnitude, and often have harmful, even life-threatening, outcomes. Yet, the extent to which people believe that combined hazards can present synergistic risks is unclear. We present the results of two experimental studies aimed at addressing this issue. In both studies, participants examined synergistic and additive risk scenarios, and judged whether these were possible. The results indicate that the proportion of people who believe that synergistic risks can occur declines monotonically as the magnitude of the synergistic risk increases. We also find that people believe, despite scientific evidence to the contrary, that certain hazard combinations are more likely to present additive or weakly synergistic risks than synergistic risks of higher magnitudes. Furthermore, our findings did not vary as a simple function of hazard domain (health vs. social), but varied according to the characteristics of the specific hazards considered (specified vs. unspecified drug combinations). These results suggest that many peoples' beliefs concerning the risk attributable to combined hazards could lead them to underestimate the threat posed by combinations that present synergistic risks, particularly for hazard combinations that present higher synergistic risk magnitudes. These findings highlight a need to develop risk communications that can effectively increase awareness of synergistic risks.

1.1. Introduction

1.1.1. Overview

Accumulating scientific evidence shows that different hazards can interact to produce a risk that is greater than the sum of the risk produced by each hazard operating individually. Such *synergistic risks* can vary greatly in magnitude and have been identified for a range of hazard combinations across several domains (Chadwick, Waller & Edwards, 2005; Grossarth-Maticek et al., 2000; Hashibe et al., 2009; Keall, Firth & Patterson, 2004; Raine, Brennan & Mednick, 1997). However, much less is known about lay individuals understanding of synergistic risks.

A number of recent studies have assessed peoples' perceptions of synergistic *health* risks. Although some results suggest that peoples' perceptions are consistent with synergistic models (Bonnin-Scaon, Lafon, Chasseigne, Mullet & Sorum, 2002 ; Eiser, Reicher & Podpadec, 1995 ; French, Sutton, Kinmonth & Marteau, 2006 ; Hampson, Andrews, Lee, Lichtenstein & Barckley, 2000 ; Hampson, Andrews, Barckley, Lee & Lichtenstein, 2003), the majority of studies indicate that these risks are perceived as additive (i.e., equal to the sum of the perceived risk attributable to each constituent hazard) or less than additive (i.e., sub-additive) (Bonnin-Scaon et al., 2002; French, Gayton, Burton, Thorogood & Matreau, 2002; French, Marteau, Sutton & Kinmonth, 2004; French et al., 2006; Hampson, Andrews, Lee, Foster, Glasgow & Lichtenstein, 1998; Hampson et al., 2000, 2003; Hermand, Mullet & Coutelle, 1995; Hermand, Mullet & Lavieville, 1997; Hermand, Mullet, Sorum & Tillard, 2000). The complex task of drawing conclusions from these mixed findings is compounded by the use of conflicting definitions of 'synergy' (French et al., 2004, 2006; Hampson et al., 2000, 2003) and concerns regarding the validity of the metrics employed (French et al., 2002, 2004, 2006).

Consequently, it remains unclear whether lay perceptions of synergistic health risks are inconsistent with scientific evidence, or whether such inconsistencies have been erroneously identified as a result of the techniques employed to measure and interpret individuals' risk assessments.

In addition, previous studies have not investigated peoples' *beliefs* concerning the risks posed by combined hazards and, specifically, whether people believe combined hazards can present synergistic risks. Clearly, if someone believes it is not possible for hazard combinations to present synergistic risks, then he/she is not able to make veridical risk assessments (i.e., assessments that are consistent with scientific evidence) for a combination that presents a greater than additive risk. Alternatively, someone who believes that combined hazards can present synergistic risks may, for other reasons, not assess the combined risk accurately. Furthermore, previous studies do not assess whether peoples' beliefs concerning the risk attributable to combined hazards vary according to different synergistic risk magnitudes and for synergistic risks that occur outside the health domain.

Our studies aimed to fill these important knowledge gaps by assessing whether lay individuals believe combined hazards can present synergistic risks. Specifically, we assessed whether these beliefs varied according to different magnitudes of synergistic risk, the hazard domain, and for different hazard combinations from the same domain (i.e., different drug combinations). Our objective was to provide new insights into lay individuals' beliefs concerning the risk attributable to combined hazards, and to determine whether individuals need help to better understand synergistic risks.

1.1.2. Synergistic Risks

Consistent with the epidemiological and pharmacological literatures (Rothman, 2002; Sellers, Schoedel & Romach, 2006), the operational definition of a 'synergistic risk' used here is: where two or more hazards interact to produce a combined risk that is greater than the sum of the risk from their separate effects. Synergistic risks that conform to this definition are often identified in epidemiological, toxicological, and pharmacological studies. For example, several studies demonstrate a synergistic risk of laryngeal cancer for individuals who use both alcohol and tobacco (Flanders & Rothman, 1982; Saracci, 1987; Talamini et al., 2002), and some pharmaceutical combinations have been associated with synergistic risks for toxicity of the central nervous system and for gastrointestinal bleeding (Chadwick et al., 2005; Delaney, Opatrny, Brophy & Suissa, 2007). Synergistic risks not only arise from physical interactions, but also from interactions involving psychological, environmental, and physiological factors (Eysenck, Grossarth-Maticek & Everitt, 1991; Grossarth-Maticek et al., 2005; Keall et al., 2004; Marrero et al., 2005; Van Os, Pedersen & Mortnesen, 2004). For example, Raine, Brennan, and Mednick (1997) showed that the likelihood of a male committing a violent crime before reaching adulthood increases synergistically if his birth involved medical complications (e.g., mother suffering from pre-eclampsia, umbilical cord prolapse, etc.) *and* he is subject to maternal rejection. Hence, there is increasing evidence that synergistic risks are not unique to the interaction of physical hazards. Furthermore, synergistic interactions have been shown to result in a wide range of risk magnitudes, from those just above additive (Silbeberg, 1990) to a 19-fold increase in risk (Castellsague et al., 1999) or even higher (Zambon et al., 2000). Evidently, synergistic interactions can vary in terms of the characteristics of the constituent hazards, the domain of the adverse outcome, and the resultant risk magnitude. Many of these synergies have harmful, even life-threatening, outcomes. Consequently, there is a clear need to improve our understanding of peoples' beliefs concerning synergistic risks.

1.1.3. Perceptions of Synergistic Risks

Several studies have aimed to assess peoples' perceptions of the risk posed by combined hazards that present synergistic *health* risks (Bonnin-Scaon et al., 2002; Eiser et al., 1995; French et al., 2000, 2002, 2004, 2006; Hampson et al., 1998, 2000, 2003; Hermand et al., 1995, 1997, 2000). A key motivation for these studies was to obtain descriptive accounts of the perceived risk for certain hazard combinations, so that the relative effects of risk communications concerning these combinations could be assessed. These studies predominantly relied upon data gathered in the form of subjective 'risk' estimates, obtained via visual-analogue *rating scales* (e.g., respondents put a mark on a Likert-type scale or a 20cm line, both having anchored labels such as "no risk" and "very high risk" at either end), *101-point scales* (i.e., a number between 0 and 100 is written down, or a mark is placed on a line that has 101 equal intervals with anchored labels at either end), or *unbounded scales* (i.e., respondents provide a risk score ranging from 0 to infinity, relative to a more familiar exemplar that is given a score of 100). However, as discussed below, important concerns have been expressed regarding the validity of these scales.

The majority of studies employed *rating* scales (French et al., 2000, 2004, 2006; Hampson et al., 1998, 2000, 2003; Hermand et al., 1995, 1997, 2000), with results typically indicating that the participants held sub-additive models of risk. However, the authors identified a number of issues that raised concerns about the validity of the findings. For example, when using the scale, participants often rated both constituent hazards as “highly risky” (e.g., providing a ‘6’ on a 7-point scale for each hazard). This left no room on the scale for estimates representing a greater-than-additive estimate for the two hazards when combined (i.e., a “ceiling effect”). In addition, this metric consistently yielded sub-additive models of risk irrespective of the hazard combination, and irrespective of whether participants had reviewed intervention materials detailing the additive or synergistic risk attributable to that combination (French et al., 2006). Moreover, the risk judgments obtained in two studies indicate that, despite reviewing intervention materials stating that the hazard combination presents a synergistic risk, participants believed one constituent hazard (e.g., radon) would reduce the risk attributable to the other constituent hazard (e.g., smoking) (Hampson et al., 1998, 2000). These recurring problems with the rating scales led French and colleagues to conclude that such scales do not elicit valid measures of the perceived risk for combined hazards (French et al., 2004, 2006).

Two studies which employed the rating scales discussed above have reported perceptions consistent with a synergistic model of risk (Hampson et al., 2000, 2003). However, these studies defined ‘synergy’ as “*rating the combined hazard as significantly more risky than the more risky of the two hazards*” (Hampson et al., 2000, p. 247). Consequently, perceptions reported as consistent with a synergistic model of risk may actually be consistent with an additive or sub-additive model (French et al., 2004). As the rating scales employed did not possess equal interval properties, the data produced in these studies cannot be used to calculate whether the risk ratings for the combined hazards were greater than the sum of the ratings. Consequently, these studies do not enable us to determine whether lay judgments of synergistic risks can be veridical (French et al., 2004, 2006).

The majority of studies assessing perceptions of synergistic risks, which have employed interval scales ranging from 0 to 100, conclude that participants' risk perceptions are consistent with additive or sub-additive models of risk (Bonnin-Scaon et al., 2002, French et al., 2002, 2004, 2006). These findings occurred irrespective of whether (a) the scientific evidence shows that the hazards under consideration interact additively or synergistically and (b) the participants had been exposed to intervention materials. One study, employing a 101-point scale, did find perceptions consistent with a synergistic model (Bonnin-Scaon et al., 2002). However, this was after participants had completed a complex one-to-one training procedure that lasted 60-90 minutes and involved 160 training cards and feedback from the experimenters regarding use of the scale. Consequently, it is unclear whether perceptions of synergistic risk were found due to the success of the training method or because participants implicitly learned to use the scale to express information as directed by the experimental conditions. Hence, the combined evidence from studies using 101-point scales can be interpreted in two ways: (a) where perceptions of risk are consistent with a synergistic risk model, the 101-point scales can only accurately document this after a person has received tuition on use of the scale or (b) people do not perceive the risk from combined hazards as synergistic, unless they are exposed to an intensive intervention technique. Unfortunately, this ambiguity prevents us from using these studies to draw clear conclusions about lay understanding of synergistic risks.

The results of two studies employing an 'unbounded' interval scale indicated that individuals employ additive risk models (French et al., 2002, 2004). However, the hazard combinations considered may not, according to epidemiological research, present synergistic risks in practice. Consequently, these results may suggest that (a) the participants' risk perceptions were veridical and the metric employed found valid evidence of this or (b) the scale itself biased responses to yield additive models of risk. The former conclusion is supported by Eiser et al. (1995): data obtained using an unbounded scale showed participants held synergistic models of risk for the combination of tobacco smoke and radon exposure. Why the participants' perceptions appeared to be in line with the epidemiological data (Reif & Heeren, 1999) remains uncertain, but Eiser et al. speculated that it may have been attributable to the increased media attention given to the combination around the time of their study. The only other study we have found that employed the unbounded scale was conducted by French et al. (2006). The results suggested that, irrespective of whether scientific evidence indicates a hazard combination presents an additive or synergistic risk, participants' perceptions appeared to follow a weakly synergistic model. Despite French et al.'s efforts to assess the scale's validity, by presenting participants with educational interventions detailing the difference between the additive and synergistic combinations, the results did not determine whether (a) the intervention materials were ineffective and the scale captured valid representations of the participants' risk perceptions or (b) the scale biased responses to yield weakly synergistic models of perceived risk for both combinations. Thus, whether the unbounded scale provides a valid means of assessing the veridicality of lay awareness of synergistic risks has not been established.

In summary, researchers have gone to great lengths to identify valid means of assessing peoples' risk perceptions for combined hazards. However, there remain a number of unresolved uncertainties regarding the validity of the data obtained in these studies. Consequently, it remains difficult to draw firm conclusions about the extent to which people understand that specific hazard combinations present synergistic risks.

1.1.4. The Present Research

1.1.4.1. Rationale for the Research

Several researchers have asserted that 'perceptions of risk' are not typically pre-formed as numerical subjective probability estimates, but are better characterized as basic beliefs about hazards and the personal relevance of the threats posed (Downs, Bruine de Bruin, Murray & Fischhoff, 2004; Eiser, 1994; French et al., 2004; Sjoberg, 2000; Windschitl, 2002). These assertions are supported by the findings of several studies (Boeije & Janssens, 2004; Brown & Morley, 2007; French & Hevey, 2008; Windschitl, 2002). Thus, in investigating perceptions of synergistic risks, it is important to develop our understanding of peoples' *beliefs* concerning the risks posed by combined hazards; specifically, whether individuals believe that combined hazards can present synergistic risks. After all, if an individual does not believe that the risk attributable to a hazardous combination can be greater than the sum of the risk attributable to each constituent hazard then, it is likely that he/she will underestimate the risk (i.e., employ an additive or sub-additive model).

We explore the extent to which people believe combined hazards present synergistic risks and assess whether these beliefs differ: (a) for synergistic risks of varying magnitudes, (b) relative to beliefs concerning whether the combined hazards present additive risk, (c) according to the domain of the hazard combination, and (d) for different hazard combinations from the same domain (i.e., different drug combinations).

1.1.4.2. Possibility judgments for assessing beliefs regarding the risk attributable to combined hazards

Understanding whether an event is possible is a vital skill when making judgments that transcend the physical evidence at hand (Legrenzi, Girotto, Legrenzi & Johnson-Laird, 2003; Shtulman, 2009; Shtulman & Carey, 2007; Subbotsky, 2010). For instance, knowing whether it is possible to become pregnant from having unprotected sex just once may determine whether one faces the dilemma of an unplanned pregnancy (Downs et al., 2004). Studies show that the ability to differentiate between possible and impossible events is well-developed in adults (Shtulman, 2009; Shtulman & Carey, 2007; Subbotsky, 2010). For example, Shtulman (2009) found that adults and young children consistently denied the possibility of impossible events (e.g., unscrambling a scrambled egg), but only adults consistently judged improbable events (e.g., walking on a telephone wire), as possible. Both Shtulman and Subbotsky explain this by asserting that, when evaluating the possibility of a claim or an event that transcends the evidence at hand, adults make judgments consistent with what they believe can occur in the world and, unsurprisingly, veridical knowledge of what can occur is typically more advanced in adults (Subbotsky, 2010; Shtulman, 2009).

In our two studies, we investigate peoples' beliefs concerning the concept of synergistic risk. To assess these beliefs, we present participants with written scenarios that, for example, describe a synergistic risk, and we ask them to judge whether the described risk magnitude for a particular hazard combination is possible or impossible. In employing this approach, we, as in the 'possibility judgment' research outlined above, are asking the participants to evaluate whether the event described is consistent with what they believe can occur. Therefore, these judgments provide a measure of the participants' beliefs concerning the risk concept (e.g., synergistic risk) depicted in each scenario.

1.1.5. Hypotheses

No previous study which has explored the perception of synergistic risks has specifically assessed 'beliefs' as the principal dependent variable. Consequently, we are unable to draw directly from empirical findings in formulating the directions of our hypotheses. We, therefore, base our predictions on *inferences* drawn from studies concerning perceptions of synergistic risks, and from the wider risk perception literature.

Previous research has suggested that lay individuals are predominantly inclined to rely on sub-additive or additive assessments of risk for combined hazards (Bonnin-Scaon et al., 2002; French et al., 2002, 2004, 2006; Hampson et al., 1998, 2000, 2003; Hermand et al. 1995, 1997, 2000). One interpretation of these findings could be that lay individuals arrive at such assessments because they do not believe that the risk attributable to the combination can be synergistic. Consequently, we test the following s*ynergistic risk hypothesis*: People believe that it is *impossible* that combined hazards present synergistic risks, and *additive risk hypothesis*: People believe that it is *possible* that combined hazards present additive, rather than synergistic risks.

Evidence suggests that, when individuals demonstrate an awareness of the synergistic risk presented by a particular combined hazard, they tend to underestimate the magnitude of the risk (Eiser et al., 1995; French et al., 2006; Hampson et al., 2003). Hence, we test the following *risk magnitude hypothesis*: As the synergistic risk magnitude presented by a combined hazard increases, more people believe that the synergistic risk is impossible.

There is a dearth of studies assessing lay understanding of non-health related synergistic risk. Consequently, we assess beliefs concerning the concept of synergistic risk across two domains: health and social. Previous studies have shown that risk perceptions and risk-taking behaviours can vary according to domain (Weber, Blais & Betz, 2002; Zuckerman & Kuhlman, 2000), but it remains unclear whether lay beliefs concerning synergistic health and non-health risks differ. Based on the anecdotal observation that synergistic risks in the health (cf. the social) domain are better publicized (e.g., harmful drug-drug interactions publicized by doctors, etc.), we test the following *risk domain hypothesis*: Beliefs that a synergistic risk is possible in the health (cf. the social) domain will be significantly greater.

1.2. Study 1

To test the hypotheses, we presented participants with five written scenarios: four describing synergistic risks, each of differing magnitude, and one describing an additive risk. Some participants reviewed scenarios that depicted a hazard combination that posed a risk in the health domain and others reviewed scenarios in the social domain. Participants were asked to judge whether each scenario was possible.

1.2.1. Method

1.2.1.1. Participants

One-hundred-and-ten first-year undergraduate management students (46 women, 63 men, and one who did not indicate their gender) were recruited by verbal invitation during a first-week lecture at a UK University. This invitation was given on two separate occasions, with participants completing the experiment after one of the two announcements. The participants were offered the opportunity to be entered into a draw to win one of four £25 prizes. The participants mean age was 18.9 years (*SD* = 1.24).

1.2.1.2. Design

The experiment followed a 5 (risk magnitude: additive, additive x 1.25, additive x 2.5, additive x 5, additive x 10) x 2 (risk domain: health, social) mixed factorial design, with the first factor as within-subjects and the other factor as between-subjects.[1]

1.2.1.3. Materials

Each of the written scenarios presented to participants comprised three statements (see Appendix One). The first statement described the relative frequency of one adverse outcome given exposure to a specific individual hazard (e.g., *for people who use 'Drug A' once-a-day, there is a side-effect of a 1 in a 100 chance of having a heart attack in any given year*). In order to convince participants of the validity and reliability of the data, the statement specified that the frequency data had been found by four recent scientific studies, (all participants were made aware that these studies were fictitious *after* the second testing session was complete).[2] The second statement described the relative frequency of the same adverse outcome given exposure to a different individual hazard (e.g., *for people who use 'Drug B' once-a-day, there is a side-effect of a 3 in a 100*

[1] At each of the five levels of risk magnitude there was no significant main effect for gender (Bonferroni correction: 0.05 / 5 = 0.01) in either Studies 1 or 2, χ^2s (1) <= 6.75, *p* => 0.02. Therefore, gender was not included in the main analyses of either study.

[2] In Study 1, participants were asked to provide a written description of the reasoning underlying each possible/impossible judgment (written data not reported in this paper). As intended by the design of the scenarios, none of the participants reported judging the scenario impossible based on a belief/concern that the information described in Statements One or Two was impossible.

chance of having a heart attack in any given year). Once again, the statement specified that the frequency data was derived from four separate scientific studies.

The third statement in each scenario described the relative frequency for the same adverse outcome given exposure to a combination of the hazards from statements one and two. The frequency specified was either an additive or a greater-than-additive combination of the frequencies described in statements one and two. The third statement did not purport to be a product of scientific research; thus, encouraging participants to make their own assessment of the validity and reliability of this information.

Each scenario was followed by the question "*In consideration of the information in 'Statement One' and 'Statement Two', is it possible that 'Statement Three' is correct?*" Participants were asked to provide a "*yes/no*" response. In each scenario, the relative frequency data described in statements two and three was adjusted so that the risk magnitude attributable to the combined hazards varied on five levels, from 'additive' to 'additive x 10' (see Table 2).

Table 2. A summary of the relative frequency data explicitly described in each scenario and the risk magnitude implicitly described in each scenario

Scenario	Relative frequency in statement one (single hazard 1)	Relative frequency in statement two (single hazard 2)	Relative frequency in statement three (hazards 1 and 2 combined)	Implicit risk magnitude from the combined hazards
A	1/100	1/100	2/100	Additive
B	1/100	3/100	5/100	Additive x 1.25 [a]
C	1/100	1/100	5/100	Additive x 2.5 [a]
D	1/100	3/100	20/100	Additive x 5 [a]
E	1/100	1/100	20/100	Additive x 10 [a]

[a] Synergistic risk

'Health' and 'social' versions of the five scenarios were created. The health scenarios described the relative frequency of heart attacks for people using either one of two non-specified drugs (e.g., Drug A *or* Drug B) and using both drugs (e.g., Drug A *and* Drug B). The health scenarios were, therefore, representative of the empirical evidence showing that synergistic risks can be attributable to drug combinations (Chadwick et al., 2005; Sellers et al., 2006). The social scenarios described the relative frequency of male adolescents committing a violent crime given that their birth involved medical complications *or* that they experienced maternal rejection, and for those who experienced *both* of these factors. The social scenarios were, therefore, representative of the empirical evidence showing that a synergistic risk of violent crime can be attributable to the combination of maternal rejection and birth complications (Raine et al., 1997). The design of the scenarios in these two domains only differed in terms of the descriptions of the hazards and outcomes (e.g., relative frequency data, names and years of referenced studies, etc. were identical).

To assess the reliability of the scenario design, participants were presented with each of the five scenarios twice, with identical relative frequency data in each presentation. On the second presentation, the names of the referenced authors in each scenario were changed to minimize the chance of participants identifying the scenario as a replica. Consequently, each participant responded to a total of ten scenarios: five original scenarios, each describing a different risk magnitude for a given hazard combination and five duplicates.

1.2.1.4. Procedure

The scenarios were presented to each participant via an online survey system on one of two days in the same week.[3] The system randomly allocated participants to receive only the health scenarios (n = 59) or the social scenarios (n = 51). Participants were instructed that they had an unlimited time to respond to the scenarios and that they should evaluate the data in each scenario independently from the other scenarios. The system then presented each participant with the scenarios in a random order.

1.2.1.5. Analysis

[3] To assess the internal validity of the data, responses for individuals participating on the first day were compared to the responses of individuals participating on the second day. The two groups did not differ significantly (Bonferroni correction: 0.05 / 10 = 0.005) in their responses for each of the five original and duplicate scenarios, χ^2s (1) <= 1.51, p => 0.22.

As the dependent variable in Study 1 was dichotomous ("*yes*" = 1, "*no*" = 0) and not normally distributed, non-parametric tests were employed to test the hypotheses. When selecting the tests, consideration was given to the experimental design (i.e., within- or between-subjects) that had been employed to gather the data to address each hypothesis. To assess the synergistic risk hypothesis, binomial tests were used to determine whether the proportion of scenarios judged possible differed to a test value of zero; the expected value for a sample that judged all the synergistic risk scenarios as impossible (one binomial test was performed for each level of synergistic risk magnitude). For the additive risk hypothesis, McNemar's tests were used to assess whether the proportion of additive risk scenarios judged possible was significantly greater than the proportion of synergistic risk scenarios judged possible (one test performed for each level of synergistic risk magnitude). To address the risk magnitude hypothesis, a Cochran's Q test was performed to assess whether there was a significant variation in the proportion of scenarios judged possible across each of the four different levels of risk magnitude. Where significant variation was identified, *post hoc* analysis was conducted using McNemar's tests to determine between which levels of risk magnitude significant differences existed. Finally, in relation to the risk domain hypothesis, the dataset was initially split into two subsets using domain as a grouping variable (i.e., separate datasets of health scenarios and of social scenarios). A Cochran's Q test was then performed for each subset to identify whether any variation in the proportion of synergistic risk scenarios that were judged possible (across each of the four risk magnitude levels) was attributable to one or both domains. *Post hoc* Chi-Square tests were then employed to examine whether the proportion of synergistic health risk and synergistic social risk scenarios that were judged possible at each level of risk magnitude were significantly different. Bonferroni corrections were used whenever multiple comparisons were made.

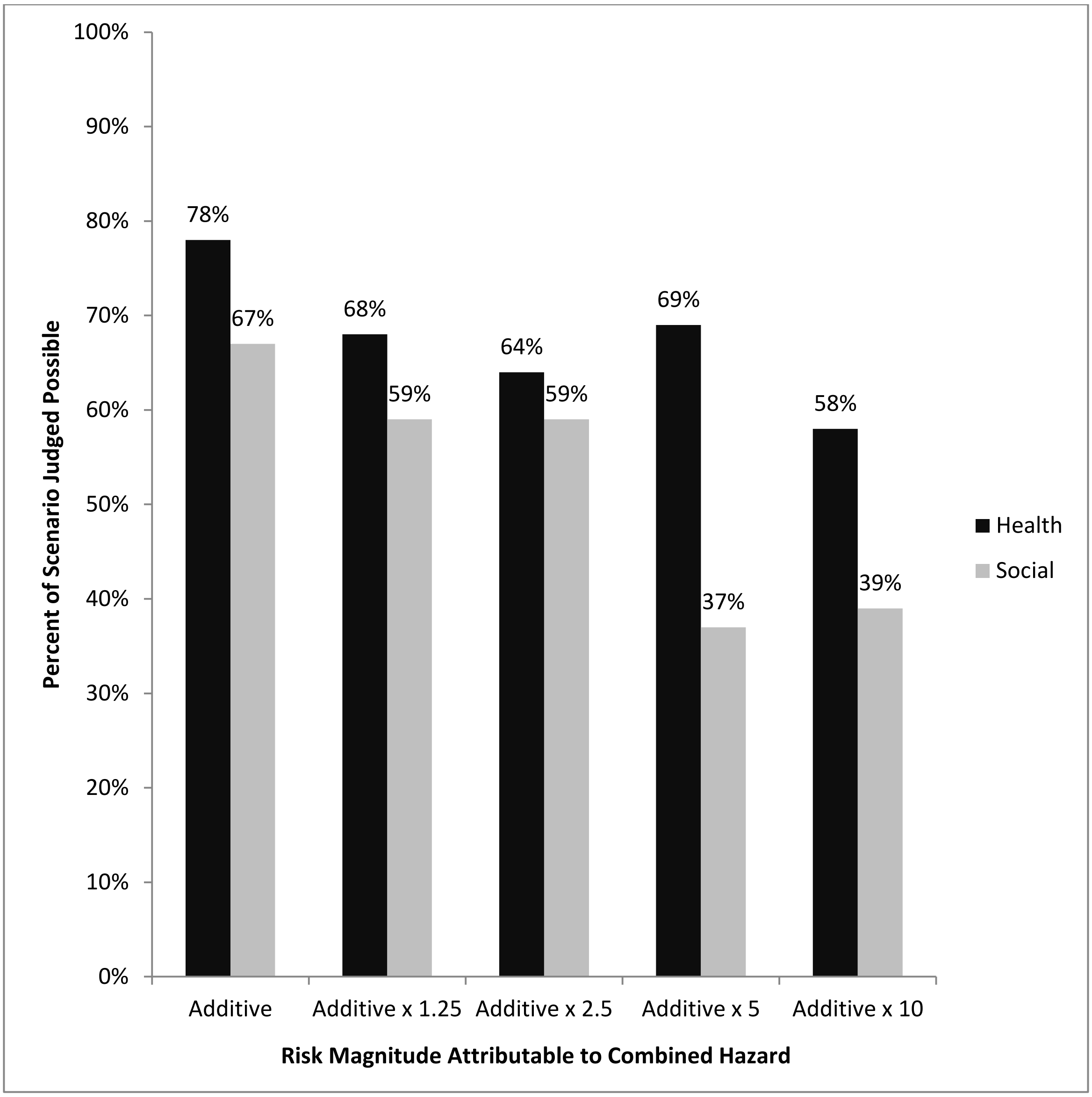
1.2.2. Results

1.2.2.1. Scenario Reliability

Responses to each scenario and its corresponding duplicate scenario demonstrated a strong positive correlation, as assessed using Phi's correlation coefficient: Scenario A (Additive), $\phi = 0.67$, $p < 0.001$; Scenario B (Additive x 1.25), $\phi = 0.69$, $p < 0.001$; Scenario C (Additive x 2.5), $\phi = 0.65$, $p < 0.001$; Scenario D (Additive x 5), $\phi = 0.75$, $p < 0.001$; and Scenario E (Additive x 10), $\phi = 0.80$, $p < 0.001$. The overall agreement percentage between responses obtained from all the original and duplicate scenarios was 87%, and for the Scenarios A – E the agreement percentages were 87%, 85%, 84%, 87% and 90%, respectively.

In light of the established reliability of the scenarios, only the responses to the original scenarios were selected for the main analyses which is reported here (analysis of the responses to the duplicate scenarios led to results that replicated the same support/rejection of our four hypotheses). The percentages of health and social scenarios judged possible for each of the five scenarios are shown in Figure 1.

Figure 1. Study 1 (N = 110): Percentages of Scenarios Judged Possible (separate bars shown for health and social conditions



1.2.2.2. Synergistic Risk Hypothesis

Binomial tests showed that for each of the four levels of synergistic risk magnitude the proportion of synergistic risk scenarios judged possible (Additive x 1.25, 64%; Additive x 2.5, 62%; Additive x 5, 53%; Additive x 10, 49%) was significantly different from the test value of 0, *p*s < 0.001. Thus, inconsistent with the synergistic risk hypothesis, a significant proportion of synergistic risk scenarios were judged *possible* instead of *impossible*.

1.2.2.3. Additive Risk Hypothesis

McNemars' tests (using a Bonferroni correction: 0.05/4 = 0.0125) identified that the proportion of Additive scenarios judged possible (73%) was not significantly different to the proportion of Additive x 1.25 or Additive x 2.5 scenarios judged possible, χ^2 (1) <= 3.56, *p*s => 0.06. However, the proportion of Additive scenarios judged possible was significantly greater than the proportion of Additive x 5 scenarios, χ^2 (1) = 9.03, $p < 0.01$, and Additive x 10 scenarios judged possible, χ^2 (1) = 14.88, $p < 0.001$. Hence, the additive risk hypothesis was partially supported. That is, the results showed that people believe that combined hazards present additive risks rather than synergistic risks of *higher magnitudes*.

1.2.2.4. Risk Magnitude Hypothesis

A Cochran's Q test identified significant variation in the proportion of synergistic risk scenarios judged possible across each of the four risk magnitude levels, χ^2 (3) = 13.30, $p < 0.01$. This result indicated that the proportion of synergistic risk scenarios judged possible decreased significantly as the risk magnitude increased. Hence, the risk magnitude hypothesis was supported. *Post hoc* analyses using McNemar's tests (with a Bonferroni correction: 0.05/6 = 0.008) identified that the difference between the proportion of Additive x 2.5 scenarios judged possible and the proportion of Additive x 10 scenarios judged possible was significant ($p = 0.003$); all other comparisons between each two levels of risk magnitude were not significant (*p*s => 0.014).

1.2.2.5. Risk Domain Hypothesis

A Cochran's Q test performed on the health scenarios dataset revealed no significant variation in the proportion of health scenarios judged possible across the four synergistic risk magnitudes, χ^2 (3) = 4.48, p > 0.05. By contrast, a Cochran's Q test performed on the social scenarios dataset identified significant variation in the proportion of social scenarios judged possible across the four synergistic risk magnitudes, χ^2 (3) = 18.72, p < 0.001. In other words, the earlier observation that "*the proportion of synergistic risk scenarios judged possible decreased significantly as the risk magnitude increased*" (see 2.2.4.) was largely attributable to the social scenarios and not the health scenarios. These results supported the risk domain hypothesis. *Post hoc* analysis using Chi-square tests (with a Bonferroni correction: 0.05/4 = 0.0125) identified a significant difference between the proportion of Additive x 5 health scenarios and Additive x 5 social scenarios that were judged possible, χ^2 (1) = 11.47, p = 0.001. At each of the three other levels of risk magnitude, no other significant differences were identified between the health and social scenarios, χ^2 (1) <= 3.71, p => 0.04.

1.2.3. Discussion

The results of Study 1 show that as the synergistic risk magnitude increased, the proportion of scenarios judged 'possible' decreased. However, this monotonical decline in 'possible' judgments was largely attributable to responses to the social scenarios; suggesting that more participants believed that the 'health' hazard combination (i.e., two drugs interacting) could present higher magnitudes of synergistic risk than the 'social' hazard combination. That is, many of the participants' beliefs were consistent with the scientific data that shows drug-drug interactions can vary in magnitude from 'additive' to higher than 'additive x 10' (Chadwick et al., 2005; Sellers et al., 2006). However, the data also indicates that many participants believed that the risk model attributable to the social combinations would mostly likely be an additive model, which is at odds with the scientific data.

The health scenarios in Study 1 described the adverse effects of combining two *non-specific* drugs. These non-specific descriptions allowed participants to consider the combination to be comprised of any two drugs (e.g., combinations involving illegal drugs, prescription drugs, etc.). By contrast, the hazard descriptions in the social scenarios were more specific (i.e., birth complications and maternal rejection), offering little scope for participants to make subjective interpretations of the hazards being described. This difference in the specific/non-specific descriptions used between the two scenario domains may have contributed to the identified difference in judgments between participants in the health and social conditions. That is, the effect of domain may have been attributable to variation in either (a) the participant's beliefs concerning synergistic risks across the two domains or (b) the specific (non-specific) description of the social (health) hazard combination. Study 2 was conducted to investigate this issue and replicates Study 1. However, in Study 2 the health scenarios were altered to describe two specific drugs that, when combined, present a synergistic health risk.

1.3. Study 2

1.3.1. Method

1.3.1.1. Participants

A separate sample of 131 first-year undergraduate management students (70 women, 61 men) were recruited by verbal invitation during a lecture at a UK University. The mean age of participants was 19.0 years (*SD* = 1.9).

1.3.1.2. Design

As for study 1, the experiment followed a 5 (risk magnitude: additive, additive x 1.25, additive x 2.5, additive x 5, additive x 10) x 2 (risk domain: health, social) mixed factorial design, with the first factor as within-subjects and the remaining factor as between-subjects.

1.3.1.3. Materials

The design of both the health and social scenarios replicated the design used in Study 1. However, on this occasion, the health scenarios described the relative frequency of gastrointestinal bleeding for people using either "*the painkilling drug Aspirin*", "*the anti-blood-clotting drug Warfarin*", or both of these drugs. The health scenarios were a representation of the empirical evidence showing that a synergistic risk of gastrointestinal bleeding can be attributable to the combined use of aspirin and warfarin (Ament, Bertolino & Liszewski, 2000; Delaney et al., 2007).

1.3.1.4. Procedure

The materials were administered in a pencil-and-paper format during one testing session. Sixty-two participants reviewed health scenarios only and 69 reviewed social scenarios only. Within both of these groups, the scenarios were presented in a randomized order to counter potential order effects. Participants received instructions as per Study 1, and each participant responded to five scenarios.[4]

1.3.1.5. Analysis

Data analysis replicated that employed in Study 1. The data was again analysed with a view to making a further assessment of our four hypotheses.

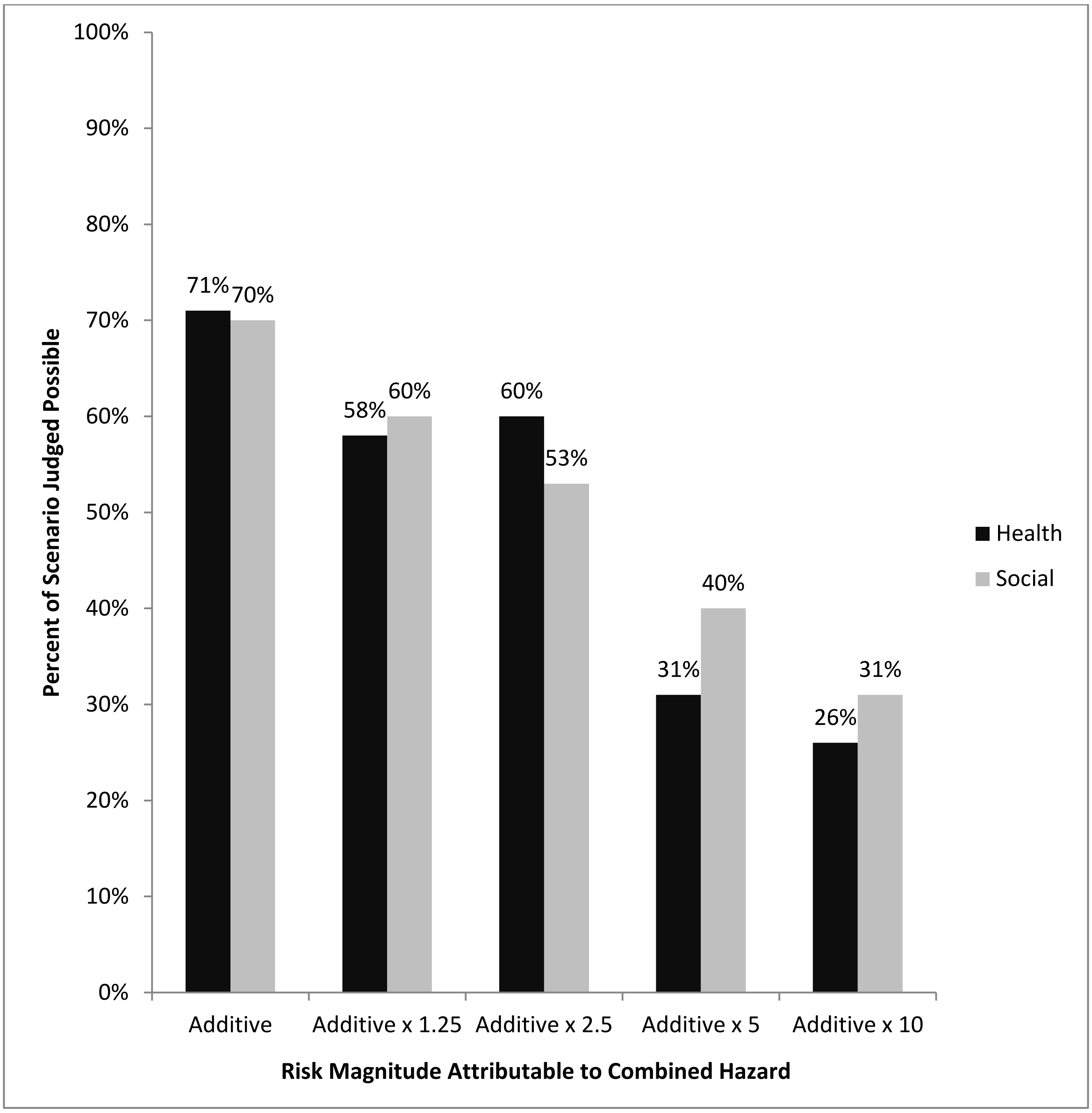
1.3.2. Results

1.3.2.1. Synergistic Risk Hypothesis

The percentages of health and social scenarios judged possible for each of the five scenarios in Study 2 are shown in Figure 2. Binomial tests identified that for each of the four levels of synergistic risk magnitude the proportion of scenarios judged possible (Additive x 1.25, 59%; Additive x 2.5, 56%; Additive x 5, 35%; Additive x 10, 28%) was significantly different from the test value of 0, ps < 0.001. As was the case for Study 1, these results were inconsistent with the synergistic risk hypothesis because a significant proportion of synergistic risk scenarios were judged *possible* instead of *impossible*.

[4] In Study 2, it was decided that the reliability of the scenarios did not require further testing. This decision was made because the reliability of the data obtained in Study 1 had been established, and was confirmed (ϕs = 0.70, $p < 0.001$) in a further repeat of Study 1 (repeated study not reported in this thesis). Hence, participants were asked to respond to the original scenarios only.

Figure 2. Study 2 (N = 131): Percentages of Scenarios Judged Possible (separate bars shown for health and social conditions)



1.3.2.2. Additive Risk Hypothesis

McNemars tests (Bonferroni correction: 0.05/4 = 0.0125) revealed that the proportion of Additive scenarios judged possible (70%) was not significantly different to the proportion of Additive x 1.25 or Additive x 2.5 scenarios judged possible, χ^2 (1) <= 5.56, *p*s => 0.02. However, the proportion of Additive scenarios judged possible was significantly greater than the proportion of Additive x 5, χ^2 (1) = 27.27, $p < 0.001$, and

Additive x 10 scenarios judged possible, χ^2 (1) = 42.56, p < 0.001. Hence, as was the case for Study 1, the additive risk hypothesis was partially supported. In particular, the results showed that more people believe combined hazards present additive risks rather than synergistic risks of higher magnitudes.

1.3.2.3. Risk Magnitude Hypothesis

Significant variations in the proportions of synergistic risk scenarios judged possible across each of the four risk magnitude levels were identified using a Cochran's Q test, χ^2 (3) = 86.70, p < 0.001. This result indicated that the proportion of synergistic risk scenarios judged possible decreased significantly as the risk magnitude increased. Hence, the risk magnitude hypothesis was supported. *Post hoc* analyses using McNemar's tests (with a Bonferroni correction: 0.05/6 = 0.008) identified that the difference between the proportion of Additive x 1.25 scenarios and Additive x 2.5 scenarios and between the proportion of Additive x 5 scenarios and Additive x 10 scenarios that were judged possible were not significant (ps => 0.08). However, all other comparisons between the proportions of scenarios judged possible for each two levels of risk magnitude were significantly different (ps < 0.001).

1.3.2.4. Risk Domain Hypothesis

A Cochran's Q test performed on the health scenarios dataset identified a significant variation in the proportion of health scenarios judged possible across the four synergistic risk magnitudes, χ^2 (3) = 42.23, p < 0.001. This finding was inconsistent with the results of Study 1. However, a Cochran's Q test performed on the social scenarios dataset revealed, as in Study 1, significant variation in the proportion of social scenarios judged possible across the four synergistic risk magnitudes, χ^2 (3) = 22.05, p < 0.001. These results showed that in both the health and social domains the proportion of synergistic risk scenarios judged possible decreased significantly as the risk magnitude increased. *Post hoc* analysis using Chi-square tests (with a Bonferroni correction: 0.05/4 = 0.0125) identified that, at each of the four magnitudes of synergistic risk, there was no significant difference between the proportion of health scenarios judged possible and the proportion of social scenarios judged possible, χ^2s (1) <= 1.40, p => 0.16. Findings from both the Cochran's Q and Chi-square tests were not consistent with the risk domain hypothesis.

1.3.3. Discussion

Generally, the results of Study 2 replicated those of Study 1. However, one important difference emerged: the interaction between risk magnitude and risk domain, which had been identified in Study 1, was not evident in Study 2. It appears that, by amending the health scenarios to feature specifically named hazards (as was the case for the social scenarios), participants responded in a virtually identical way to both the health and social scenarios. That is, as per the social scenarios in Study 1, when the synergistic risk magnitude depicted in both the health and social scenarios increased, there was a monotonical decline in the proportion of participants that believed that the scenarios were possible.

1.4. General Discussion

We have presented two studies aimed at investigating peoples' beliefs concerning hazard combinations that present synergistic risks. From our data, two important observations can initially be made in relation to this research objective. First, 47 percent of the participants expressed the belief that it is possible that the hazard combinations could present a range of two or more different synergistic risk magnitudes, and 58 percent expressed the belief that both an additive and at least one synergistic risk scenarios were possible.[5] Hence, it appears that peoples' beliefs may feature some epistemic uncertainty concerning both the risk magnitude (i.e., lower or higher magnitudes of synergy) and/or the risk model (i.e., additive or synergistic) attributable to combined hazards. Second, the results indicate that the beliefs expressed, were not on the whole, entirely consistent with the scientific data. For example, evidence shows that drug interactions can result in risk magnitudes ranging from 'additive' to higher than 'additive x 10'. However, not all of the health risk scenarios in Study 1 were judged possible. Similarly, the study by Raine et al. (1997) indicated that the magnitude of the synergistic (social) risk attributable to the interaction between birth complications and early maternal rejection is approximately 'additive x 2'.[6] However, knowledge that this synergistic risk model was attributable to the combination was not clearly evident in the

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[5] Using data from both Studies 1 and 2 (N = 241), we observed that 24 percent of participants judged *all* the synergistic risk scenarios as impossible, and 29 percent judged all synergistic risk scenarios as possible. The remaining 47 percent of participants judged some synergistic risk scenarios possible and others impossible. We also observed that, across both studies, 58 percent of participants judged both an additive risk scenario possible and at least one synergistic risk scenario possible.

[6] Raine et al. (1997, p. 1268) reported that 2/100 of individuals under 18 years of age who have suffered maternal rejection were predisposed to committing violent crime. They found this figure was 3/100 for individuals under the age of 18 who were born in circumstances involving medical complications. They also found 9/100 of individuals under 18 years of age who experienced a complicated birth *and* suffered maternal rejection were predisposed to committing violent crime. The magnitude of the risk attributable to the combined hazards is calculated here as (2 + 3) x 1.8 = 9 (i.e., additive x 1.80).

judgments provided in both of our studies. Hence, our studies show that peoples' general beliefs concerning the risk attributable to combined hazards can incorporate knowledge of both additive and synergistic models of risk, but that more specific beliefs regarding the risk attributable to particular hazard combinations are not necessarily consistent with 'objective' scientific data.

We offer two plausible explanations which may account for our finding that individuals are more inclined to believe combined hazards present additive risks or, to some extent, lower magnitudes of synergistic risk. First, research evidence shows that individuals have a preference for using the rule of addition to solve numerical problems (e.g., solving a simple subtraction problem by calculating how much should be *added* to the smaller number to arrive at the larger number) (Torbeyns, De Smedt, Peters, Ghesquiere & Verschaffel, 2011). In addition, Brown and Morley (2007) have found that individuals' estimates of perceived risk are not necessarily numerically specific, but are typically fuzzy and span a range of possible estimates. Hence, many of our participants may have interpreted our scenarios as numerical problems and, consequently, employed an addition rule for convenience and to alleviate task complexity. Then, using the addition rule as an anchor, the participants may have judged that the lower magnitudes of synergistic risk were also possible because the risk magnitude fell within a fuzzy range that was close to additive. Second, our participants may have tested the possibility of the additive and synergistic risk scenarios against their own knowledge using the availability heuristic (Tversky & Kahneman, 1973). Due to an absence of recent publicized incidents or personal experiences involving high magnitude synergistic risks, such events may have seemed less plausible (This explanation should be treated with slight caution as it relies on an untested assumption that individuals typically experience more additive risks and lower magnitudes of synergistic risks). These two interpretations of our results could also serve as a partial explanation for our finding that the proportion of the synergistic risk scenarios judged possible declined as the depicted risk magnitude increased.

It is interesting that a 'domain effect' was identified in Study 1, but not in Study 2. A logical reason for this difference is that participants in Study 1 had more freedom (cf. in Study 2) to consider drug combinations that differed, in terms of their individual and/or combined characteristics, to those featured in Study 2. The results suggest that many participants in Study 1 brought to mind possible drug combinations they considered to be "more dangerous" (i.e., combinations they considered could interact to present higher synergistic risk magnitudes). Whereas the aspirin-warfarin combination featured in Study 2 appears to have been perceived, in relative terms, as a "safer" combination; possibly because both drugs are well regulated, frequently administered by medical professionals, and are commonly used for beneficial purposes. Hence, our findings suggest that beliefs concerning the risk attributable to combined hazards do not vary as a function of the hazard-domain (i.e., Study 2), but can vary according to the specific characteristics of the constituent hazards under consideration.

It should be noted that the two hazard combinations employed within both studies had different characteristics. Specifically, the health/drug combination consisted of two physical agents that can interact to increase the likelihood of an adverse health event. By contrast, the social combination featured a bio-medical event that can combine with sociological circumstances to increase the likelihood of violent behaviour. It is, therefore, of particular interest that the participants' beliefs concerning the risk attributable to both combinations in Study 2 did not differ. It is possible that the results are an artefact of the data collection method employed or that people simply find higher risk magnitudes less believable. However, neither of these interpretations appears appropriate as the responses to the scenarios in Study 1 show that (a) this metric can yield different response patterns for different hazard combinations and (b) many people find higher synergistic health risk magnitudes just as believable as lower ones. Rather, in interpreting why the beliefs expressed for both hazard combinations in Study 2 were so similar, we suggest that, given the very different characteristics of the two combinations, this may be a general pattern of beliefs that individuals hold for most hazard combinations when they experience epistemic uncertainty regarding the level of risk the combination presents. However, as seen in Study 1, a departure from this pattern of beliefs may be observed for certain hazard combinations that people understand can present more extreme magnitudes of synergistic risk (e.g. as one might expect for the combination of alcohol and driving [Hampson et al., 2003]).

Previous studies employing the "*more valid*" (French et al., 2004, p.391) metrics (i.e., 101-point and unbounded scales) have often identified either additive or weakly synergistic models of perceived risk (Bonnin-Scaon et al., 2002; Eiser et al., 1995; French et al., 2002, 2004). These findings are consistent with our results, in that these risk magnitudes/models appear to be those that most people believe are generally attributable to combined hazards (We cannot comment on peoples' beliefs about sub-additive models, as these were not assessed in our studies). More specifically, our results indicate this is the case for hazard combinations that people have little prior cause to consider as "dangerous combinations". Hence, unless people are informed to the contrary, it seems unlikely that they would arrive at veridical risk magnitude estimations for hazard combinations that present higher synergistic risk magnitudes.

1.4.1. Limitations and Future Directions

To our knowledge, the two studies we have presented are the first to employ 'possibility judgments' as a means of assessing peoples' beliefs about the risk attributable to combined hazards. This approach appears sensitive to variations in peoples' beliefs regarding the risk magnitudes (and whether these magnitudes represent additive or synergistic models of risk) attributable to different hazard combinations. The approach also avoids asking participants to provide single, specific risk estimates that they may not have constructed previously and which, therefore, may be susceptible to contextual variations (Brown & Morley, 2007; Windschitl, 2002). Nonetheless, we acknowledge that there are some potential limitations to our studies that could be addressed in future research. First, the 'possibility judgments' method requires individuals to make explicit risk assessments, which may differ from the more intuitive and affect-based judgments that people make in everyday life (Slovic, Peters, Finucane & MacGregor, 2005). With this in mind, researchers could attempt to develop methods for assessing individuals' intuitive beliefs concerning synergistic risks and to identify how these may influence risk-related behaviours in more naturalistic contexts. Second, we employed a within-subjects design to assess the influence of the risk magnitude variable. It is possible that this approach could have elicited a 'demand effect', with participants identifying the subtle differences between the scenarios and, subsequently, providing responses that they believed were consistent with the researchers' expectations. Hence, future studies could employ a between-subjects design to determine whether individuals' 'possibility judgments' are prone to such an effect. Third, future studies that employ possibility judgments may benefit from manipulating the scenarios so that participants are also presented with sub-additive risk magnitudes and/or more hazards that vary in terms of their domain and characteristics. As illustrated by the variation between the responses obtained for the health scenarios in Studies 1 and 2, care should be taken in the design of scenarios to ensure that participants only consider the hazard combination(s) intended by the researcher. Finally, researchers could explore whether, and to what extent, beliefs differ amongst participants with less homogeneity than the samples we employed. For instance, samples with more diverse socio-demographic characteristics (e.g., age, education, etc.) may have different levels of knowledge and experience which, consequently, could influence their beliefs about the risk attributable to combined hazards.

1.5. Conclusion

Our findings indicate most individuals believe that hazard combinations which in practice present synergistic risks, will present additive risks. More specifically, far fewer individuals appear to believe such combinations can present high magnitudes of synergistic risk. We suggest that it is perhaps only when people understand that specific combinations can be "highly dangerous" that most believe the combination may be highly synergistic. This highlights the importance of identifying effective risk communication messages that alert people to the dangers (i.e., synergistic risk) posed by combining specific hazards. Without such messages, many people may underestimate the extent to which they, or others, are exposed to potential harm by certain combined hazards. Consequently, identifying message formats and contents that can effectively inform people about synergistic risks remains an important area for future research.

Chapter Two: Subjective Judgments of Synergistic Risks: A Cognitive Reasoning Perspective

Abstract

Mounting evidence that certain hazard combinations present synergistic risks for adverse outcomes, including violent crime, cancer, and species extinction, highlights the importance of understanding the risk attributable to combined hazards. However, previous studies indicate that individuals often misjudge synergistic risks as additive or sub-additive risks, and there is little research which explores the cognitive reasoning that may lead individuals to make such judgments. This study aims to fill this gap. Participants were asked to review several scenarios that described the risk magnitude presented by a combined hazard. They were required to judge whether each scenario was possible and to explain the reasoning that led to their judgment. The results show that many participants demonstrated an awareness of synergistic risk and that their reasoning was typically characterized by rudimentary knowledge of an underlying causal mechanism for the increased risk (e.g. a chemical reaction between drugs). Conversely, several participants adopted a line of reasoning that precluded the concept of synergistic risk. Many of these participants appeared to employ an additive model of risk, corresponding to the notion of 'adding' one hazard to another. Contrary to much previous research, we found little evidence to indicate that people tend to employ a sub-additive model of risk for combined hazards. Implications for future research and the improvement of risk communications concerning synergistic risks are discussed.

2.1. Introduction

2.1.1. Overview

The importance of adopting self-protective behaviours is highlighted by research that shows modifiable lifestyle factors (e.g. smoking, physical inactivity, etc.) are a leading cause of death across the world (Mokdad, Marks, Stoup, & Gerberding, 2004; World Health Organization, 2002). However, public awareness of the impact of lifestyle on illness and mortality still remains low (Sanderson, Waller, Jarvis, Humphries, & Wardle, 2009). This is of concern when it is considered that numerous studies examining the relationship between risk perceptions and risk behaviours have found that an awareness of personal vulnerability is a key factor that influences progression towards adopting precautionary behaviours (Brewer, Weinstein, Cuite, & Herrington, 2004; Eiser & Arnold, 1999; Floyd, Prentice-Dunn, & Rogers, 2000; Milne, Sheeran, & Orbell, 2000).

Understanding the magnitude of one's vulnerability to undesirable outcomes is of particular importance when it is considered that exposure to certain combinations of hazards can result in a risk which is greater than the sum of the risk attributable to each constituent hazard alone (Saracci, 1980). Such 'synergistic risks' have been identified for a large number of hazard combinations, and across several domains. For example, the combination of alcohol and tobacco has been shown to present a synergistic risk of both oesophageal and laryngeal cancer (Flanders & Rothman, 1982; Zambon et al., 2000), and some drug-drug interactions lead to synergistic risks of gastrointestinal bleeding and toxicity of the central nervous system (Chadwick, Waller, & Edwards, 2005). Furthermore, synergistic risks have also been reported in ecology and sociology studies. For example, male babies born in medically complicated circumstances, who also experience maternal rejection, present a synergistic risk of committing violent crime during adolescence (Raine, Brennan, & Mednick, 1997). In addition, habitat destruction, genus traits, and global warming can interact to present synergistic risks of species extinction (Davies, Margules, & Lawrence, 2004; Hannah, Midgley, Hughes, & Bomhard, 2005).

The value of understanding the severity of the threat posed by synergistic risks is highlighted by studies concerning the combination of radon (a naturally occurring radioactive gas) and smoking. Specifically, Darby et al. (2005) have reported that the risk of developing lung cancer for smokers' increases 25-fold if also exposed to radon in the home, and Gray, Read, McGale, and Darby (2009, p.340) report that six out of seven UK deaths attributable to the smoking-radon combination could be prevented by avoiding exposure to either hazard alone. Evidently, precautionary behaviours are a viable means of reducing or avoiding the threats posed by synergistic risks. However, several studies suggest that when most people make risk judgments for hazard combinations, which in practice present synergistic risks, they tend to judge the risk as being 'additive' (i.e. equal to the sum of the risk attributable to each constituent hazard) or 'sub-additive' (i.e. less than the sum of the risk attributable to each constituent hazard) (for a detailed taxonomy of these studies see French, Sutton, Kinmonth, & Marteau, 2006). This raises the concern that many individuals underestimate their vulnerability to the threats presented by exposure to certain combined hazards and, in turn, may diminish their adoption of appropriate avoidance/precautionary behaviours. Furthermore, failure to appreciate the synergistic risk posed by certain hazard combinations may impede the public's motivation to demand political, social and economic action to address the risk presented by these combinations (see Leiserowitz, 2006).

In light of the above discussion, it is surprising that there is little research that explores the reasons *why* individuals might make non-veridical risk judgments for combined hazards (i.e. judgments that do not correspond to objective, scientific risk assessments). More specifically, little is known about the lines of cognitive reasoning individuals employ to arrive at risk judgments for combined hazards. It has been speculated that exploration of these reasoning processes may reveal why an individual judges that a combination presents either a sub-additive, additive, or synergistic risk (French et al., 2006; Hampson et al., 1998). Hence, we present a study that (a) identifies the lines of reasoning individuals employ when judging the risk for combined hazards and (b) assesses the ways in which such reasoning may contribute to risk judgments for combined hazards that are veridical or non-veridical. Consequently, we are able to make empirically informed recommendations for risk communication approaches that may elicit appropriate lines of reasoning and, in turn, help individuals make more accurate assessments of synergistic risks.

2.1.2. Subjective Judgments of Synergistic Risks

Several studies have attempted to assess individuals' perceptions of synergistic health risks (e.g., French, Marteau, Sutton, & Kinmonth, 2004; Hampson, Andrews, Barckley, Lee, & Lichtenstein, 2003; Hermand, Mullet, & Lavieville, 1997). Although some of these studies found evidence that individuals hold synergistic models of perceived risk for some hazard combinations (e.g., Eiser, Reicher, & Podpadec, 1995; French et al. 2006), most studies have found that individuals' adhere to sub-additive or additive risk models (e.g., French, Marteau, Senior, & Weinman, 2000; Hampson et al., 1998; Hermand, Mullet, & Coutelle 1995; Hermand et al., 1997; Hermand, Mullet, Sorum, & Tillard, 2000). However, the studies that have assessed perceptions of synergistic health risks have predominantly relied upon data obtained using one of three types of psychometric scales (i.e., Likert-type rating scales, 101-point scales, or unbounded scales) which, as several of the authors of these studies have indicated, may produce misleading results (French et al. 2004, 2006; Hampson et al., 2003).

When using the Likert-type scales, participants have often rated both constituent hazards as "highly risky" (e.g. providing a '6' rating on a 7-point scale for each hazard). Consequently, this left no room on the scale to represent a greater-than-additive estimate for the two hazards when combined. This recurrent finding indicates people may use the Likert-type scales to represent their 'level of concern' regarding the hazards rather than to reflect probability estimates (Borland, 1997). To address this issue, researchers assessing subjective risk judgments for combined hazards have also employed 101-point scales (i.e. participants provide a single risk estimate on an equal interval scale ranging from 0 to 100) and unbounded scales (i.e. participants provide a numerical risk rating, ranging from 0 to infinity, relative to a familiar risky activity that is given a risk rating of 100). As with the Likert-scale, researchers have raised concerns that these two scales may not accurately reflect an individual's beliefs concerning the risk attributable to combined hazards (French et al., 2004, 2006). For example, French et al. (2006), when assessing the validity of all three scales, provided one group of participants with written and graphical materials that explained that a hazard combination presented an additive risk and another group with materials in an identical format that explained that a different combination presented a synergistic risk. Results showed that risk estimations did not vary according to the hazard combination groupings, but varied according to the rating scales participants used. French et al. concluded that there was insufficient evidence to confirm that either scale possessed sufficient 'sensitivity' to detect variations in individual's perceived risk for combined hazards, but that risk judgments can vary according to the scales employed (see also French et al., 2004). Consequently, the validity of the findings obtained using the three psychometric scales discussed above remains uncertain.

2.1.3. The Cognitive Reasoning Underlying Judgments of Synergistic Risks

Taken at face value, the studies that have employed one or more of the rating scales discussed above indicate that many individuals may not understand that certain hazard combinations present synergistic risks. Yet, these studies provide little evidence to indicate why this could be the case. In particular, risk ratings themselves do not reveal the respondent's line(s) of reasoning for arriving at a risk rating that indicates that they do/do not believe the hazard combination presents a synergistic risk. It has been suggested by Hampson et al. (1998, p.349) that individuals may engage in particular lines of cognitive reasoning which impede veridical risk judgments for combined hazards:

> Better understanding of the process by which people arrive at their assessments of the combined risk would be valuable. … Future research should explore these various aspects of the "cognitive algebra" involved in processing risk perceptions with a view to developing risk communications that can modify this algebra.

To our knowledge, the notion that particular lines of cognitive reasoning may influence the accuracy of risk judgments for combined hazards remains empirically untested. At present, the previous literature only provides limited insight into the cognitive reasoning individuals employ when making judgments related to synergistic risks. For example, Hampson et al. (1998) conducted interviews to assess lay individuals' mental models of the risk attributable to a combination of radon and smoking. They found that individuals attached several emotional labels to the hazard combination (e.g. apprehensive, scary, etc.), and that they lacked knowledge about radon. However, the study did not reveal how the participants arrived at their overall assessment of risk for the hazard combination. Additionally, in a study by Hermand et al. (1997), 64% of participants reported, via a multiple-choice question, that they were aware, when judging the risk for the combined use of tobacco and alcohol, that the 'multiplicative rule' could be applied (i.e. that risks for constituent hazards could be multiplied, rather than added, to determine the risk for a combined hazard). Despite this, the participants generally employed a sub-additive model of risk when providing subjective risk ratings for the combination of alcohol and tobacco. However, these risk ratings were made using one of the Likert–type scales, the validity of which has been questioned (see above). It is, therefore, difficult to draw firm conclusions as to whether individuals can, or do, apply a 'multiplicative rule' when judging the risk for combined hazards.

Without empirical evidence concerning the cognitive reasoning that takes place when people judge risk for combined hazards, our understanding of these cognitive processes can only be partially illuminated by the literature concerning broader, related, psychological processes. For example, evidence in support of Information Integration Theory (Anderson, 1981) has shown that individuals can employ adding, averaging, and multiplying rules when making judgments concerning the integration of multiple valuations and attributes (Anderson, 1974). However, it has not been established whether such 'cognitive algebra' is employed, bypassed, or applied erroneously, when individuals judge the risk attributable to combined hazards. Similarly, evidence supporting Fuzzy-Trace Theory (Reyna & Brainerd, 1995a, 1995b) indicates that individuals often employ gist-based cognitions (i.e., a reliance on the vague gist of information and memories) that help them make risk-related judgments, rather than employing deliberative, and explicitly verbatim (e.g. quantitative), cognitions (Brown & Morley, 2007; Reyna & Brainerd, 2008). However, it is unclear to what extent the cognitive reasoning that takes place when risk judgments are made for combined hazards tends to be based on explicit, numerical calculations or on more heuristic, gist-based cognitions. Furthermore, 'knowledge' has been identified as an important component of perceived risk (Johnson, 1993; Waller, McCaffery, & Wardle, 2004), but there is little evidence indicating how prior knowledge of specific hazards might be employed when arriving at subjective risk judgments for combined hazards.

2.1.4. Objectives of this Study

This study aims to fill important gaps in the literature identified above. Specifically, we seek empirical insight into the following aspects of the cognitive reasoning that underlies individuals' assessments of risk for combined hazards:

a) The lines of reasoning employed.
b) The extent to which individuals' reasoning involves deliberative, numerical computations, or qualitative, gist-based cognitions.
c) The extent to which individuals employ prior knowledge.
d) The extent to which an individual's line of reasoning is affected by the specific hazard combination and the risk magnitude under consideration.

2.2. Method

2.2.1. Participants

One-hundred-and-twenty-nine first-year undergraduate management students (56 women, 72 men, and one who did not indicate their gender) were recruited by verbal invitation during lectures at a large UK University. Participants were given the opportunity to be entered into a draw to win one of four £25 prizes. The mean age of participants was 18.9 years (*SD* = 1.27).

2.2.2. Materials

Each participant examined five written scenarios that all described the risk attributable to a hazard combination. Participants were asked to judge whether or not each scenario was possible and to provide a written explanation elucidating the cognitive reasoning underlying each judgment. The purpose of asking participants to judge whether each scenario was possible, was to motivate them to conduct a mental search for information to determine whether the scenarios were consistent with their knowledge of what can occur in the world (Shtulman, 2009; Shtulman & Carey, 2007; Subbotsky, 2010). Hence, the judgments would provide a measure of whether or not the risk concepts (e.g. synergistic risk) depicted in each scenario were counter-intuitive to the participants (Subbotsky, 2010). In addition, the written explanations for each judgment would provide an explicit account of the cognitive reasoning participant employed when assessing the risk concept depicted in each scenario.

As the principal aim of the study was to assess participant's reasoning concerning the possibility that some hazard combinations present synergistic risks, four of the five scenarios employed implicitly depicted a synergistic risk. The magnitude of the synergistic risk was varied across each of the four scenarios to ensure the responses obtained would reflect potential variation in participants' beliefs concerning the extent to which synergistic risk magnitudes can vary (e.g. where an individual believes a hazard interaction can lead to a 2-fold increase in risk but does not believe, inconsistent with scientific evidence, that a 20-fold increase is possible). Four scenarios were employed to ensure the study assessed responses to a broad range of synergistic risk magnitudes without over-burdening participants with too many judgment tasks. A single additive risk scenario was also presented to participants. This scenario was employed as a 'control' to facilitate relative comparisons between responses to the synergistic risk scenarios and a non-synergistic risk scenario.

Each scenario featured three statements (see Appendix Two). 'Statement One' specified the relative frequency of an adverse outcome following exposure to a particular single hazard (e.g., *for individuals who use 'Drug G' once-a-day there is a side-effect of a 1 in a 100 chance of having a heart attack in any given year*). In order to encourage the participants to infer that the validity and reliability of the data was incontrovertible, the statement indicated that the frequency data had been identified in four recent empirical studies (participants were only informed *after* the experiment that the referenced studies were fictitious). 'Statement Two' specified the relative frequency of the identical adverse outcome given exposure to a different single hazard (e.g., *for individuals who use 'Drug H' once-a-day, there is a side-effect of a 3 in a 100 chance of having a heart attack in any given year*). Once again, the statement indicated that the frequency data had been found in four recent studies.

In each scenario, 'Statement Three' specified the relative frequency of the same adverse outcome following combined exposure to the hazards from Statements One and

Two. The relative frequency described in Statement Three was either an additive or greater-than-additive (i.e. synergistic) composition of the frequencies specified in Statements One and Two. The frequency data in Statement Three was not described as being identified by empirical research; thus, allowing participants to assess its validity and reliability.

Following each scenario was the question "*In consideration of the information in 'Statement One' and 'Statement Two', is it possible that 'Statement Three' is correct?*" Participants responded either "*yes*" *or* "*no*" and provided a written account explaining why they had arrived at that judgment. For each scenario, the frequency data in Statements Two and Three was varied so that the magnitude of risk attributable to the hazards, when combined, was at one of five levels, ranging from 'additive' to 'additive x 10' (see Table 3).

Table 3. The relative frequency data described in each scenario and the risk magnitude for the hazard combination for each scenario

Scenario	*Relative frequency in Statement One for single hazard 1*	*Relative frequency in Statement Two for single hazard 2*	*Relative frequency in Statement Three for hazards 1 and 2 combined*	*Implicit risk magnitude for the combined hazard*
A	1/100	1/100	2/100	Additive
B	1/100	3/100	5/100	Additive x 1.25 [a]
C	1/100	1/100	5/100	Additive x 2.5 [a]
D	1/100	3/100	20/100	Additive x 5 [a]
E	1/100	1/100	20/100	Additive x 10 [a]

[a] Synergistic Risk

The five scenarios were produced in both ‘health’ and ‘social’ formats for two reasons. First, this ensured domain-specific awareness of synergistic risks (e.g., where an individual is aware of synergistic *social* risks, but not synergistic *health* risks) would be represented in the data obtained. Second, this enabled our study to be focused upon two domains in which there continues to be accumulating empirical identification of synergistic risks (e.g., Takahashi and Kimura, 2010; Van Os, Pedersen, & Mortensen, 2004).

The health scenarios depicted the risk of a heart attack for individuals taking one of two unspecified drugs (e.g. Drug A *or* Drug B) and for individuals taking both drugs (e.g. Drug A *and* Drug B). Hence, the health scenarios were representative of research evidence showing that drug-drug interactions can present synergistic risks (e.g. Chadwick et al., 2005). The social scenarios depicted the risk of male adolescents committing violent crime given that their birth involved medical complications *or* that they were subjected to maternal rejection, and the risk for male adolescents who experienced *both* of these circumstances. Hence, the social scenarios were designed to reflect evidence showing that the interaction of biological and sociological factors can result in a synergistic risk of violent crime (Raine et al., 1997). The design of the health scenarios and social scenarios only differed in terms of the depicted hazards and outcomes (e.g. the numerical data, the names and years of referenced studies, etc. were identical). All risk magnitudes were presented in a natural frequency format with a constant denominator of 100.

2.2.3. Procedure

An on-line survey system was used to present the scenarios to each participant on one of two days in the same week. Participants were randomly allocated to the health scenarios only (n = 65) or the social scenarios only (n = 64). Participants were advised there was no time limit (M = 20 minutes 8 seconds) and that each scenario should be assessed independently from the others. The on-line system presented each participant with the scenarios in a random order.

2.2.4. Qualitative Data Analysis

2.2.4.1. Data Coding

In analysing the participants' written responses, our objective was to identify and measure the prevalence of specific lines of cognitive reasoning concerning the risk attributable to combined hazards. This involved summarising the semantic theme of the participant's qualitative, written responses so that each response could be categorised and, therefore, counted. To achieve this, we employed Content Analysis methodology. This approach was selected as it systematically identifies, categorizes, and quantifies the characteristics of qualitative data (Neuendorf, 2002; Joffe & Yardley, 2004).

In the absence of prior qualitative studies regarding subjective judgments of the risk attributable to combined hazards, the coding categories were developed inductively from the participants' written responses. This inductive approach was consistent with content analysis methodology, which involves "*emergent coding … when no useful standard classification or coding scheme exists*" (Neuendorf, 2002, p. 195). The whole text of each participant's written response to each scenario was treated as one 'unit of analysis'. The range of codes was exhaustive (i.e. a code was developed for every unit) to ensure that all units could be included in the subsequent analyses, where required (Neuendorf, 2002).

Furthermore, each unit was assigned only one mutually exclusive code based on the holistic semantic theme of the text (Morberg-Pain, Chadwick, & Abba, 2008; Weber, 1990).

To develop an initial set of codes, 30 written responses were randomly selected from the ‘health’ group and a further 30 from the ‘social’ group. Based on the semantic themes conveyed in these 60 units, a set of codes and corresponding definitions were created. The codes/definitions were developed and refined in an iterative manner as the 60 units were examined. This resulted in a preliminary coding scheme that was subsequently tested using a further 20 written responses randomly selected from the ‘health’ group and 20 from the ‘social’ group. Subject to some minor refinements of the codes and their corresponding definitions, a final coding scheme was established that was suitable for generic application across both the health and social scenarios.

The final coding scheme featured 21 codes that comprised three alphanumeric characters (see Table 4). The codes were structured so that the first, second and third characters indicated, respectively, whether the written response (i.e. unit) related to a synergistic or additive risk scenario (i.e. ‘S’ or ‘A’ respectively), whether the scenario had been judged possible (i.e. ‘Y’ for “yes”, or ‘N’ for “no”) and the line of reasoning articulated by the participant (i.e. 1, 2, 3, etc.).

Table 4. Response category and coding units by semantic theme

Category	*Definition of semantic theme in coded unit*	*Abbreviated title (Code)*
Synergistic Risk Scenario Judged Possible	- When the two hazards/factors interact the described synergistic risk magnitude can occur	Synergistic Risk Possible (SY1)
	- The risk magnitude for the combined hazards could have occurred due to a scientific or random error	Possible Due to Error (SY2)
	- Incoherent written response	Incoherent Response (SY3)
	- No written explanation for judgment	No Written Response (SY4)
Synergistic Risk Scenario Judged Impossible	- When the two hazards/factors interact the overall risk should be the sum of the risk from each hazard operating individually	Should be Additive (SN1)
	- When the two hazards/factors interact the overall risk should be less than the sum of the risk from each hazard operating individually	Should be Sub-Additive (SN2)
	- The magnitude of the synergistic risk presented by the combined hazards is too small	Risk Magnitude Too Small (SN3)
	- The magnitude of the synergistic risk presented by the combined hazards is too large	Risk Magnitude Too Large (SN4)
	- There is insufficient evidence to determine whether the hazards combined to present a risk as described in the scenario	Insufficient Evidence (SN5)
	- It is not possible for two hazards to interact or operate simultaneously	Interaction Impossible (SN6)
	- Incoherent written response	Incoherent Response (SN7)

Table 4. (*Continued*)

Category	Definition of semantic theme in coded unit	Abbreviated title (Code)
Synergistic Scenario Judged Impossible	- No written explanation for judgment	No Written Response (SN8)
Additive Risk Scenario Judged Possible	- When the two hazards/factors interact the described additive risk magnitude can occur	Additive Risk Possible (AY1)
	- Incoherent written response	Incoherent Response (AY2)
	- No written explanation for judgment	No Written Response (AY3)
Additive Risk Scenario Judged Impossible	- When the two hazards/factors interact the overall risk should be greater than the sum of the risk from each hazard operating individually	Should be Synergistic (AN1)
	- When the two hazards/factors interact the overall risk should be less than the sum of the risk from each hazard operating individually	Should be Sub-Additive (AN2)
	- There is insufficient evidence to determine whether the hazards combined to present a risk as described in the scenario	Insufficient Evidence (AN3)
	- It is not possible for two hazards to interact or operate simultaneously	Interaction Impossible (AN4)
	- Incoherent written response	Incoherent Response (AN5)
	- No written explanation for judgment	No Written Explanation (AN6)

Only two principal lines of reasoning were identified for participants who judged the synergistic risk scenarios possible. Some participants reasoned that when the two hazards were combined the interaction could result in an increase in risk as described in the scenario; these responses were categorised as *synergistic risk possible* (SY1). Alternatively, some reasoned that the risk described could only have identified due to a methodological/random error. These responses were coded as *possible due to error* (SY2).

For judgments that the synergistic risk scenarios were impossible, six distinct lines of reasoning were identified. First, some participants reasoned that the interaction of the two hazards would result in a risk magnitude that would be the sum of the risk from each constituent hazard; these responses were coded as *should be additive* (SN1). Second, some participants reasoned that the interaction of the two hazards would result in a risk magnitude less than the sum of the risk from each constituent hazard; these responses were coded as *should be sub-additive* (SN2). Third and fourth, other participants did not specify the actual risk model they believed would be attributable to the combination, but simply stated that the described risk magnitude was either too low (coded as *risk magnitude too small*; SN3) or too high (coded as *risk magnitude too large*; SN4). Fifth, some participants did not categorically rule out the possibility that the hazards could present a risk magnitude as described in the scenario, but they stated that the scenario did not feature a sufficient quality and/or quantity of evidence to convince them that the scenario was feasible; these responses were coded as *insufficient evidence* (SN5). Finally, some participants reasoned that it was not possible for two hazards to interact with one another and, therefore, that the effects of each hazard would always be independent; this type of responses was coded as *interaction impossible* (SN6). Although this latter form of reasoning bears a similarity to the '*should be additive*' line of reasoning, the two were not considered identical, because an individual may believe two hazards cannot physically interact but could, for example, also believe that the second hazard does not increase the risk beyond that presented by the first hazard (i.e. one hazard presents a maximum level of risk that cannot be exceeded).

For the additive risk scenario, only one line of reasoning was identified for participants who judged the scenario possible. Participants reasoned that the risk attributable to the hazard combination could be the sum of the risk attributable to each hazard (*additive risk possible*, AY1). Participants who judged the additive risk scenario impossible reasoned that the combination would present a risk that was greater than the additive risk value (*should be synergistic*, AN1), or that the risk would be less than the additive risk value (*should be sub-additive*, AN2), or that the scenario did not feature sufficient evidence to be convincing (insufficient evidence, AN3), or that it was not possible for the two hazards to interact (interaction impossible, AN4).

2.2.4.2. Coding Scheme Reliability

All 645 units (129 participants x 5 written responses each)[7] were coded using the final coding scheme. In line with established practice for assessing the reliability of a content analysis coding scheme, an independent judge coded 129 randomly selected units (i.e. 20% of the dataset). Inter-rater reliability for coding both the synergistic

[7] To assess the reliability of the scenario design, participants were presented with each scenario twice. Consequently, each participant responded to a total of ten scenarios: five original scenarios and five duplicates. The internal consistency of the codes assigned to each 'original-duplicate' scenario-pair for the additive risk scenarios (Scenario A) was 'satisfactory' (α = 0.75), and was 'good' for responses to the synergistic risk scenarios (Scenarios B, C, D, and E) (αs > 0.80). Subsequently, it was decided that it was appropriate to exclude from the subsequent analysis, using random selection, participants' responses to either the original *or* the duplicate scenario.

(Cohen's κ = 0.87) and additive risk scenarios (Cohen's κ = 0.88) was good (Neuendorf, 2002). Codes assigned by the first coder were used in all subsequent analysis.

2.2.4.3. Preliminary Data Cleaning

Some participants had either failed to provide a judgment for a scenario, failed to give a written explanation for a judgment or, in a few cases, their written explanations were incoherent. Although these response-types had been assigned codes (applying the 'exhaustive coding' criteria), these units were deemed 'unusable' and eliminated from the subsequent analysis.[82] Consequently, the 439 'usable' units had been assigned to one of eight/five coding themes for responses to the synergistic/additive risk scenarios.

2.3. Results

2.3.1 Descriptive Overview of Responses

A majority of participants (65.9%) each provided a mixture of 'possible' and 'impossible' judgments across the five scenarios, with only 28.7% judging all five scenarios as possible, and only 5.4% judging all five scenarios impossible. The mean number of words articulated in each written response to each scenario was 15.20 (*SD* = 10.38), with 88.2%, 10.3% and 1.5% of responses being comprised of one, two and three sentences, respectively.

[8] The number of 'usable' and 'unusable' responses varied per participant, with some participants (n = 59) providing 'usable' responses to all scenarios and some (n = 70) providing at least one 'unusable' response. Responses for the group of participants who provided at least one 'unusable' response did not significantly differ from the group who provided only 'usable' data; this was the case for each of the four synergistic risk scenarios (χ^2s <= 4.06, *df*s <= 2, *p*s > 0.05) and the additive risk scenario (χ^2 = 0.78, *df* = 1, p > 0.05). Hence, the inclusion of the usable responses from participants who had provided at least one unusable response did not introduce a bias.

A count was performed to assess how many written responses to the synergistic risk scenarios explicitly featured numerical reasoning. Of the participants whom judged the synergistic risk scenarios possible, 5.1% of the responses featured quantitative reasoning (e.g. "*1 plus 1 may be greater than two*"), compared to 33.6% for participants whom judged the scenario impossible (e.g., "*1 + 3 = 4, not 5*"). For the additive risk scenario, 32% of participants whom judged the scenario possible articulated quantitative reasoning (e.g., "*1 + 1 = 2*"). Furthermore, such numerical reasoning was evident in 18.2% of responses provided by participants whom judged the additive scenarios impossible (e.g. "*the risks multiplied together do not cause a 2/100 chance of heart attack*").

2.3.2. Responses to the Synergistic Risk Scenarios

The proportion of each line of reasoning articulated by participants in response to each of the four synergistic risk magnitude scenarios are presented in Table 5. Overall, 59% of the synergistic risk scenarios were judged possible. The majority (58% of all responses; 98% of all responses indicating that the scenario was possible [referred to hereafter as 'possible responses']) were based on the reasoning that when the two hazards/factors interact the described synergistic risk magnitude could occur. Such reasoning for the synergistic health and social risk scenarios typically read:

"*A drug interaction could cause the risk to be increased by any amount, including up to 20 in a 100*." (Participant 5)

"*There is no set parameter for how the 2 factors interact and so when combined they may be much more likely to result in the individual committing a violent crime*." (Participant 88)

For the synergistic risk scenarios that participants judged possible, the only other form of reasoning offered (1% of all responses; 2% of all the possible responses) was that the scenario information was the product of random or scientific (e.g. methodological) error.

Table 5. Participants' judgments (possible vs. impossible) and the theme of the corresponding written responses for synergistic risk scenarios that each depicted one of four risk magnitudes

Participant's judgment of scenario	***Code assigned to participant's reasoning concerning their judgment of the scenario***	***Number (percentage) of written responses in each coding: shown for the four synergistic risk magnitudes implicitly described in the different scenarios.***				
		Additive x 1.25	***Additive x 2.5***	***Additive x 5***	***Additive x 10***	***Total***
Possible	Synergistic risk possible	50 (58.1%)	55 (64.7%)	49 (57.0%)	47 (52.8%)	201 (58.1%)
	Possible due to error	2 (2.3%)	1 (1.2%)	1 (1.2%)	1 (1.1%)	5 (1.4%)
Impossible	Should be additive	18 (20.9%)	15 (17.6%)	11 (12.8%)	15 (16.9%)	59 (17.1%)
	Should be sub-additive	1 (1.2%)	1 (1.2%)	1 (1.2%)	1 (1.1%)	4 (1.2%)
	Risk magnitude too small	7 (8.1%)	1 (1.2%)	0 (0%)	0 (0%)	8 (2.3%)
	Risk magnitude too large	1 (1.2%)	4 (4.7%)	14 (16.3%)	16 (18.0%)	35 (10.1%)
	Insufficient evidence	4 (4.7%)	5 (5.9%)	8 (9.3%)	5 (5.6%)	22 (6.3%)
	Interaction impossible	3 (3.5%)	3 (3.5%)	2 (2.3%)	4 (4.5%)	12 (3.5%)
	Total *n*	86 (100%)	85 (100%)	86 (100%)	89 (100%)	346 (100%)

Forty-one percent of participants judged the synergistic risk scenarios as impossible. The most common form of reasoning given (17% of all responses; 42% of all the impossible responses) was that when the two hazards/factors interact the overall risk should be the sum of the risk from each constituent hazard (i.e., should be additive). A typical response read:

"*Because for drug N and drug P added together (as fractions) it equals a 2 in 100 chance. Therefore 20 in a 100 is not possible."* (Participant 11)

Participants who judged the synergistic risk scenarios as impossible also offered the following lines of reasoning: the described risk magnitude was too large (10% of all responses; 24% of all the impossible responses), there was insufficient evidence in the scenario to determine that a synergistic risk was possible (6% of all responses; 15% of all the impossible responses), the two hazards cannot interact or one hazard could not influence the effect of another (4% of all responses; 10% of all the impossible responses), the synergistic risk magnitude depicted in the scenario was too small (2% of all responses; 5% of all the impossible responses), and the risk attributable to the combined hazard should be sub-additive (2% of all responses; 5% of all the impossible responses). A typical example of this latter form of reasoning being:

"*To meet both requirements (difficult birth and be rejected by mother) the probability should be less than 1 in 100.*" (Participant 102)

Across all the responses to the synergistic risk scenarios the term ‘synergy’, including its formal derivatives (e.g. synergistic, synergism, etc.), was only used by one participant and, only then, on one occasion. The participant in question had judged the scenario possible and reasoned:

“*Because it is more likely that both effects combined will have a greater effect, like a synergy effect*.” (Participant 108)

2.3.2.1. Response Patterns across the Four Different Synergistic Risk Magnitudes

The proportion of scenarios judged possible/impossible and the reasoning for those judgments remained relatively stable across the four different risk magnitude scenarios (see Table 3). The only exception concerned the proportion of participants who judged the scenarios as impossible on the basis that the depicted risk magnitude was too large (or too small); this proportion increased (decreased) substantially as the risk magnitude increased (decreased).

2.3.3. Responses to the Additive Risk Scenario

A large proportion (79% of all responses) of the additive risk scenarios were judged possible based on the reasoning that when two hazards/factors interact the resultant risk can be the sum of the risk for each constituent hazard (see Table 6); as illustrated by the following response:

“*Because each gives a chance of 1/100, so two independent chances are added together to obtain the combined chance*.” (Participant 51)

Unlike responses to the synergistic risk scenarios, none of the participants reasoned that the additive risk scenario would be possible due to a scientific or random error.

Table 6. Participants' judgments (possible vs. impossible) and the theme of the corresponding written responses for the additive risk scenario

Participant's judgment of scenario	***Code assigned to participant's reasoning concerning their judgment of the scenario***	***Number (percentage) of written responses in each coding for additive risk scenarios***
Possible	Additive risk possible	73 (78.5%)
Impossible	Should be synergistic	10 (10.8%)
	Should be sub-additive	4 (4.3%)
	Insufficient evidence	3 (3.2%)
	Interaction impossible	3 (3.2%)
	Total *n*	93 (100%)

Twenty-one percent of the additive risk scenarios were judged impossible. The most common (11% of all responses; 52% of all the impossible responses) rationale underlying this judgment was that the combined hazards/factors would present a risk greater than the sum of the constituent risks (i.e., there would be a synergistic risk). For example:

"*This is because the combination of both statements* [i.e. hazards] *arising in one instance is likely to make the probability far greater than the* [additive] *probability listed in statement 3*." (Participant 89)

Four percent (19% of all the impossible responses) of participants judged the additive risk scenario as impossible based on the reasoning, as the following example illustrates, that the combined hazards/factors would present a sub-additive risk:

"*Because when you add the two chances together they don't make something more likely to occur but less likely to occur*." (Participant 21)

Of the remaining participants, 3% (14% of all the impossible responses) judged the additive risk scenario impossible, reasoning that two hazards/factors cannot interact, and another 3% (14% of all the impossible responses) indicated that the scenarios did not present sufficient evidence to judge that the combination would present an additive risk.

2.3.4. Influence of Hazard Type on Responses to the Synergistic and Additive Risk Scenarios

Generally, responses to the social hazard combination and the health hazard combination were similar for both the synergistic and the additive scenarios. In fact, in terms of the proportions of responses assigned to each coding category, there was no significant difference between the social and health additive risk scenarios (χ^2s <= 1.52, *df* =1, *p*s >0.05). However, 66% of the synergistic health risk scenarios were judged possible on the basis that 'the two hazards could present a synergistic risk as described in the scenario' compared to only 49% for the social scenarios; a significant difference in proportions: $\chi^2 = 7.57$, $df = 1$, $p < 0.01$. In addition, whilst 8% of the synergistic social risk scenarios were judged impossible on the basis that 'it is not possible for the two factors to interact', this rationale was not provided by any of the participants responding to the synergistic health risk scenarios; a significant difference in proportions: $\chi^2 = 11.55$, $df = 1$, $p < 0.001$.

2.4. Discussion

We found that 58% of all the synergistic risk scenarios were judged possible based on reasoning that explicitly featured an awareness of the concept of synergistic risk. This indicates that many individuals do, or at least could, employ this reasoning when subjectively assessing the risk for specific hazard combinations. Consequently, it would be inappropriate to generalise from previous studies, which have indicated that individuals tend to perceive synergistic risks as sub-additive (e.g. French et al., 2000; Hampson et al., 1998; Hermand et al., 1995, 1997, 2000), that this stems from a general fallibility amongst lay individuals to comprehend, or apply their understanding of, the concept of synergistic risk. Rather, as French et al.'s (2004; 2006) empirically-supported argument indicates, sub-additive models of risk reported in previous studies might be artefacts of the Likert-type scales employed. It could be argued, in defence of the studies that have identified sub-additive models of risk, that the findings are valid representations of risk judgments which apply to the particular hazard combinations investigated. However, we suggest that this is unlikely, given that the sub-additive models were identified for a variety of different hazard combinations and were evident even after participants had been exposed to various intervention materials informing them of the synergistic risk (e.g. Hampson et al., 1998).

We noted above that the term ‘synergy’ was used by only one of the participants when explaining why they judged a particular synergistic risk combination was possible. However, terms such as ‘react’, ‘interaction’, ‘chemical reaction’, and ‘dangerous cocktail’, were frequently used by other participants who judged the synergistic risks scenarios as possible. The nature of the terminology employed by these participants suggests that, in making their assessment of the risk attributable to combined hazards, they drew upon prior knowledge, whether tacit or explicit, that multiple hazards can combine and react to create some form of increased potentiation. This would suggest that individuals who are aware of the synergistic risk attributable to specific hazard combinations may possess a risk-related ‘mental model’ (Bostrom, Fischhoff, & Morgan, 1992; Bostrom, 2008), albeit a simple one, of a causal mechanism underlying the resultant (synergistic) risk. This view is further supported by the observation that none of the participants who judged the synergistic risk scenarios as possible did so, according to their articulated reasoning, based on prior knowledge of specific objective risk estimates for the individual or combined hazards. Hence, our findings indicate that individuals may be more likely to make veridical judgments of synergistic risks if they have prior knowledge (even if it is rudimentary) of a causal mechanism that leads to an increase in risk when certain hazards are combined.

Our results also suggest that some individuals may lack knowledge of the concept of synergistic risk, with participants judging 41% of the four synergistic risk scenarios to be impossible. Although the cognitive reasoning underlying the judgments that these scenarios were impossible varied across six semantic themes, the most prevalent line of reasoning was that the two hazards/factors depicted in the scenario would actually present an additive risk. According to Anderson (1974, p. 9) this ‘additive mode’ of cognitive algebra represents the absence of a psychological interaction between the two stimuli (i.e. hazards). That is, participants in our study who adopted an additive model probably did so because they did not believe that when the two hazards were combined they would interact in a way that could affect the risk attributable to each hazard. Furthermore, we also found that a large proportion (79%) of the additive risk scenarios were judged to be possible, based on reasoning that the constituent risks would simply ‘add-up’. Thus, taken together, our data suggests that many individuals believe (unless they have specific knowledge to the contrary) that a summation of constituent risks is most likely to represent the ‘objective’ risk attributable to a combined hazard. This raises the concern that when individuals are uncertain about the ‘objective’ risk presented by a combination, they may tend to employ an additive risk model and, in doing so, arrive at non-veridical risk judgments for combined hazards that present either synergistic or sub-additive risks. Hence, there is clearly a need to identify methods of effectively communicating the risk for combined hazards that do not conform to an additive model.

We observed evidence amongst participants’ responses of both numerical and non-numerical lines of reasoning. Where participants reasoned numerically they tended to employ an additive calculation and, hence, reasoned that the additive risk scenarios were possible, but that the synergistic risk scenarios were impossible. By contrast, participants who judged the synergistic risk scenarios as possible articulated more qualitative reasoning that typically referred to a rudimentary awareness of a causal mechanism underlying the synergy. This further indicates that individuals who are not aware that hazards can interact in a manner that influences their combined effect may resort to numerical lines of reasoning as a 'best bet' approach to subjective risk assessment. This interpretation of our data reflects a tenet of fuzzy-trace theory, which indicates that deliberative, verbatim-based cognitions are often employed when limited comprehension of hazards and their associated risks inhibits a more qualitative, gist-based approach to assessing risk (see Reyna & Brainerd, 2008, p. 102).

In light of the number of studies that have indicated individuals employ sub-additive models of risk for combined hazards, it was surprising that only 2% and 4% of the synergistic and additive risk scenarios, respectively, were judged impossible based on the reasoning that the risk should be sub-additive. This finding is at odds with Hermand et al.'s (1995, p. 172) view that individuals tend to arrive at sub-additive models of risk for combined hazards because they infer that the riskier of the two hazards presents a "*maximal*" risk that is predominantly unaffected by the other hazard. Clearly, as participants in our study did not judge the possibility of scenarios depicting sub-additive risks, we cannot comment on the extent to which individuals are aware of this particular risk concept. However, we can at least assert that we found little evidence to suggest individual's reason that the risk attributable to combined hazards cannot be additive or synergistic based on a belief that one of the constituent hazards presents a maximal level of risk that cannot be exceeded.

There is accumulating evidence showing that synergistic social risks arise from interactions between biological and sociological factors (e.g. Grossarth-Maticek et al., 2000; Raine et al., 1997; Van Os, Pedersen, & Mortensen, 2004). However, our results suggest that lay awareness of such synergistic risks may be significantly less than lay awareness of synergistic health (i.e. drug-drug interaction) risks. This finding may be partially explained by evidence indicating that individuals are typically more concerned about health risks than social risks (Fischer, Morgan, Fischhoff, Nair, & Lave, 1991) and are likely to acquire knowledge of hazard interactions that present health risks from sources such as inserts in drug-packages (Jungermann, Schutz, & Thuring, 1988) and the media (Eiser et al., 1995). By contrast, similar information concerning synergistic social risks may be less available. Furthermore, it could be argued that developing a rudimentary understanding of how two drugs can interact to increase risk may be less challenging than understanding how sociological conditions interact with biological factors to increase risk. Consequently, lay mental models of the casual mechanism underlying 'bio-social' synergistic risks may be less developed because information about such issues is less available and because the interaction may be less easily understood.

We found that the proportion of synergistic risk scenarios judged to be impossible, based on the view that the described 'risk magnitude was too high (too small)', increased (decreased) as the risk magnitude increased. This suggests that some individuals recognise that a synergistic risk may arise when hazards are combined, but they believe that the combined risk should not exceed a, seemingly arbitrarily-defined, magnitude. It may be that this occurs because such individuals have less prior knowledge that hazards can interact to produce synergistic risks of higher magnitudes. This interpretation would go some way towards explaining the results of studies in which participants demonstrated an awareness of the synergistic risk that may arise from particular hazard combinations (Eiser et al., 1995; French et al., 2006), but where their judgments of the synergistic risk magnitudes were lower than those observed in epidemiological studies.

2.4.1. Limitations and Future Directions

Some research has indicated that many individuals do not typically think about numerical probabilities when making subjective assessments of risk (Boeije & Janssens, 2004; French & Hevey, 2008). Consequently, the provision of numerical data in our study may have influenced some participants to reason mathematically in a manner that they may not have done had they made the judgments in a more naturalistic context (i.e. introducing something akin to a 'framing effect'). However, as it was only a minority of participants whom articulated reasoning that featured explicit mathematical calculations, it appears most participants were not influenced to reason numerically simply because the risks described in the scenarios were presented in a numerical format. Nonetheless, future studies could employ scenarios that feature qualitative descriptions of synergistic risks to explore whether numerical descriptions of risk may influence some individuals to think about combined risks mathematically.

It could also be argued that the presentation of the scenarios may have elicited a demand characteristic, with participants becoming more inclined to infer that each scenario must be possible because, otherwise, it would not have been presented by the experimenters. The observation that the proportion of our participants that judged all five scenarios possible (28.7%) was greater than the proportion that judged all five scenarios impossible (5.4%) could be taken as evidence in support of this demand characteristic. However, it could equally have been the case that more participants judged all five scenarios as possible because this is arguably a more veridical interpretation of the scenarios. Furthermore, empirical studies concerning possibility judgments conducted by Shtulman (2009) and Shtulman & Carey (2007) indicate that adults employ a high standard of discrimination when assessing whether a claim/event is possible or impossible. For example, they found that adults will not judge a claim/event impossible simply because it is highly improbable (e.g. walking on a telephone wire). Nevertheless, future studies could address concerns about a potential demand characteristic by asking participants to judge scenarios that are unequivocally impossible (to determine whether participants are inclined to judge such scenarios as possible simply because the experimenters have presented them). Equally, future studies could amend the wording of the scenario question to ask whether the respondent believes each scenario is *im*possible rather than possible (to assess whether the question wording influences individuals reasoning regarding the possibility of the scenarios).

In terms of their age and educational background, our undergraduate sample was not representative of a cross-section of the general population. Therefore, the responses obtained in our study may not reflect the type of responses one might expect from groups with more diverse socio-demographic characteristics. For example, as a result of their educational experiences, our sample may have greater knowledge of interaction effects between different factors. Consequently, awareness of synergistic interactions may have been unrepresentatively high amongst this young group. Conversely, in the case of adverse drug-drug interactions, one might expect awareness of this issue to be greatest amongst an older sample of adults, as a greater proportion of older (cf. younger) individuals regularly take several different medications (see Routledge, O'Mahoney, & Woodhouse, 2003). Hence, we acknowledge the possibility that future research which employs a more representative section of the population may obtain results that differ to those reported here. However, it is also important to note that findings from previous studies give little cause to believe that student samples judge the risk for combined hazards in a manner that differs to other populations. For example, undergraduate samples were used in two studies by French et al. (2000; 2002) where participants assessed the risk attributable to combined hazards. Irrespective of the psychometric scales employed in these studies, the results showed that the undergraduates judged the risks as either additive or sub-additive. These findings are consistent with a majority of other studies concerning risk judgments for combined hazards where more representative samples of wider communities have been employed (see French et al., 2006). Nonetheless, future research concerning the cognitive reasoning underlying risk judgments for combined hazards may benefit from recruiting probability samples to negate any concerns that the characteristics of the sample may bias the results obtained.

Our findings suggest that risk communications aimed at improving individuals' understanding of the synergistic risk attributable to certain combined hazards should convey details of the causal mechanism (e.g. pharmacodynamics) involved. Essentially, this would represent 'completing' the individual's 'incomplete' mental model for the target hazard combination (Fischhoff, 2009). The efficacy of developing risk communications aimed at 'completing mental models for hazardous processes' is well documented (e.g. Atman, Bostrom, Fischhoff, & Morgan, 1994; Bostrom, 2008), suggesting that its application to the communication of synergistic risks is suitable for empirical assessment. However, risk communication content that only features details of the mechanisms underlying synergistic risk may not be sufficient by itself. Additional content, outlining the risk (i.e. conditional probability of a specific adverse outcome) attributable to a combined hazard relative to the sum of the constituent risks, may also be necessary. Such supporting content would serve to illustrate the extent to which the underlying mechanism increases risk magnitudes beyond the sum of the constituent risk magnitudes (illustrating that the risk is 'greater than additive' is clearly important in light of our finding that many individuals appear to have a preference for an additive risk model).

2.5. Conclusion

In summary, our study has provided clear evidence of the different lines of cognitive reasoning that may contribute to veridical or non-veridical risk judgments for combined hazards. From this insight, we have been able to make empirically informed recommendations for risk communication approaches that may help individuals to avoid particular lines of reasoning that may lead them to underestimate their vulnerability to synergistic risks. Avoiding such underestimations of risk is important, as it could help individuals to adopt appropriate avoidance/precautionary behaviours and become more motivated to demand action to address the pronounced threat presented by certain hazard combinations.

Chapter Three: Developing and Testing a Composed Format to Assess Subjective Risk Judgments for Combined Hazards: Helping to Understand Non-experts' and Domain-experts' Assessments of Synergistic Health Risks

Abstract

To address the need for valid methods of assessing individual's judgments of synergistic risks, we developed a new method which requires risk judgments to be made in a 'composed' format (i.e., the risk judgment for a combined hazard is explicitly made *relative* to the risk attributable to each constituent hazard). We argue that this approach improves upon the traditional 'decomposed' format (i.e., the risk judgment for a combined hazard is made separately to the judgments for each constituent hazard) and present two studies which test the composed format's criterion, face and discriminant validity. In the first study, non-experts used the composed format to make risk judgments for three combinations that present synergistic health risks: alcohol-driving, aspirin-clopidogrel and radon-tobacco. In the second study, a comparison was made between the judgments of domain-experts (i.e., independent drug prescribers) and non-experts for the aspirin-clopidogrel drug combination. Results from the studies demonstrated that the composed format can identify different trends in risk judgments between (a) the different hazard combinations presented to non-experts, and (b) the non-experts and domain-experts for the same hazard combination. Importantly, these findings indicate the composed format is a valid metric for the assessment of subjective risk judgments for combined hazards. Furthermore, the results suggest that whether an individual understands that a combined hazard presents a synergistic risk may depend on several

guiding factors that include domain-specific knowledge and judgmental experience concerning the combination.

3.1. Introduction

3.1.1. Overview

Single adverse health outcomes (e.g., heart disease) can be caused by a variety of different hazards (e.g., obesity, poor diet, physical inactivity, etc.), but it is not uncommon for individuals to be exposed to more than one of these hazards at one time (Burton & Tiffany, 1997; Yusuf, Giles, Croft, Anda, & Casper, 1998). It is, therefore, of particular concern that the interaction of certain hazards results in a health risk which is greater than the sum of the health risk attributable to each of the constituent hazards (i.e., the hazard combinations presents a 'synergistic risk'). For example, research has identified a synergistic risk of developing lung cancer for individuals who are regularly exposed to both radon (a naturally occurring radioactive gas) and tobacco smoke (Barros-Dios, Barreiro, Ruano-Ravina & Figueiras, 2002; Darby et al., 2005; Pershagen et al., 1994), and many medicinal drug combinations present synergistic risks of adverse health outcomes, such as gastro-intestinal bleeding and toxicity of the central nervous system (e.g., Bell, 1998; Chadwick, Waller, & Edwards, 2005; Hylek, Heiman, Skates, Sheehan & Singer, 1998). The need to learn more about the extent to which individuals understand this important health issue is highlighted by the scientific communities' sustained identification of hazard combinations that present synergistic health risks (e.g., Ben et al., 2011; Loomba et al., 2010; Takahashi & Kimura, 2010).

A clear concern is that if individuals underestimate the threat posed by synergistic health risks then, consequently, they will not be motivated to adopt appropriate precautionary behaviours (French et al. 2006) or to demand political, social and economic action to address this issue (Leiserowitz, 2006). Similarly, where policy-makers and regulators do not recognize that certain hazard combinations present synergistic risks, there is a concern that they may fail to implement policies and strategies that are proportionate to the threat(s) posed (Berenbaum, 1989; Cogliano, 1997). The legitimacy of these concerns is upheld by the findings of studies that have investigated individual's risk estimates for hazard combinations that present synergistic health risks. Specifically, a majority of these studies found that individuals' estimates were consistent with either additive (i.e., equal to the sum of the constituent risks) or sub-additive (i.e., less than the sum of the constituent risks) models of risk (for a comprehensive taxonomy see French Sutton, Kinmonth & Marteau, 2006). However, the authors of several of the studies exploring subjective judgments of synergistic risks have questioned the validity of the previous findings, arguing that the participants' judgments may have been artefacts of the psychometric scales employed (French, Marteau, Sutton & Kinmouth, 2004; French et al., 2006; Hampson, Andrews, Lee, Lichtenstein & Barckley, 2000). For example, French et al. (2006) found that risk estimates for the same hazard combination varied according to whether participants used a nine-point, 101-point, or unbounded scale. In addition, their findings also indicated that the sensitivity of the three scales may not be sufficient to detect different risk models (i.e., sub-additive, additive, or synergistic) for different hazard combinations (see French et al. [2002, 2004, 2006] for a thorough analysis and review of the validity of the metrics employed in previous studies). Consequently, few firm conclusions can be made concerning the extent to which subjective judgments of synergistic risks are consistent with scientific risk assessments.

Without metrics that provide valid assessments of subjective risk judgments for combined hazards, there is uncertainty regarding public awareness of the synergistic risks to which they may be exposed. Furthermore, an absence of valid metrics prohibits reliable empirical assessment, via pre- and post-intervention measures, of the relative effectiveness of risk communications aimed at educating individuals about synergistic risks (Hampson et al., 2000). Consequently, even when concerted efforts are made to inform people about particular synergistic risks, uncertainty regarding the impact on public understanding will still exist. Thus, there is clearly a need to identify valid methods of assessing subjective estimates of the risk attributable to hazard combinations.

To address this need, we developed and tested a new approach to assess individual's risk judgments for combined hazards. We drew on the extant literature to provide a rationale for both the design and evaluation of this new method, and we employed the approach in two studies that allowed us to confirm the method's criterion, face, and discriminant validity. Incidentally, our second study is, to the best of our knowledge, the first experiment to make an empirical comparison of non-experts' and domain-experts' subjective judgments for a hazard combination that presents a synergistic health risk. The findings from both studies have enabled us to make important contributions to understanding differences in the extent to which non-expert and domain–experts' risk judgments for combined hazards are veridical (i.e., consistent with scientific risk assessments), and to identify the factors that may influence these risk judgments.

3.1.2. Using a Composed Format to Assess Risk Judgments for Combined Hazards

To improve the calibration of subjective judgments involving multiple probability estimates, an approach known as decomposition-recomposition can be employed (Goodwin & Wright, 2010). In this procedure, a judgment task involving multiple subjective probability estimates is broken-up (decomposed) into individual judgments and then recombined mechanistically (recomposed). The underlying assumption of this approach is that task complexity is reduced and, thus, the calibration of judges' estimates can be improved. In some circumstances, this technique has been shown to enhance the accuracy of probability judgments (Edwards Phillips, Hays & Goodman, 1968; Wright, Rowe, Bolger & Gammack, 1994). However, Wright, Saunders and Ayton (1988) found that this is not always the case, and it has been proposed that this may arise when the decomposition-recomposition approach frames the task in a manner that is inappropriate to the judgment task, or when it renders the task unfamiliar to the judge (Goodwin & Wright, 2010; Wright et al., 2009).

Previous studies investigating peoples' risk judgments for combined hazards have obtained risk estimates from participants in a decomposed form. That is, participants have made separate (decomposed) risk estimates for each constituent hazard and for the combined hazard. The researchers have then compared (mechanistically recomposed) the three risk estimates to determine whether the individual's risk estimate for the hazard combination is less than (sub-additive), equal to (additive), or more than (synergistic) the sum of the participants' risk estimates for each constituent hazard. However, we argue that it is vital that participants are required to provide risk judgments for combined hazards in a composed format. That is, the judgment task should be presented in such a way that the respondent *explicitly* makes a risk judgment for the combined hazard *relative* to the risk attributable to each constituent. By employing this 'composed task' approach, the respondent is, therefore, required to articulate whether he/she believes the hazard combination presents a risk that is less than, equal to, or more than the sum of the risk presented by each constituent hazard.

Our argument for using a composed format (which makes explicit to participants exactly what beliefs/judgments they should represent in their responses), is also supported by a number of studies, which clearly demonstrate that when it is not made explicitly clear to participants exactly what beliefs/judgments they should represent in their response they often respond to risk-related judgment tasks in a way that is not intended by the researcher (for a review see Windschitl, 2002). For example, Fischhoff and Bruine de Bruin (1999) found, across multiple datasets, that there was a disproportionately high number of respondents who selected 50% on a probability scale, which Fischhoff and Bruine de Bruin identified as respondents using the 50% option to represent uncertainty (e.g., "I'm not sure; it's a 50-50 chance"). Also, Borland (1997) identified that respondents often used probability scales to represent subjective concern (i.e., the extent to which the individual is worried about a hazard), rather than to provide probability estimates. Such evidence highlights that, when it is not made explicit to a participant what beliefs/judgments he/she should represent in his/her response, there is the possibility that the participant will provide data that reflects beliefs/judgments that differ from those under investigation. This issue may be particularly relevant to research concerning risk judgments for combined hazards. For instance, if a respondent is aware (either explicitly or tacitly) that a combination presents a synergistic risk, it cannot be assumed that he/she will appreciate that the risk estimates he/she provides should clearly illustrate that the risk magnitude he/she attributes to the hazard combination is greater than the sum of the risk they attribute to each constituent hazard. The design of our composed format for assessing subjective risk judgments for combined hazards overcomes this issue.

3.1.3. Assessing the Criterion Validity of the Composed Risk Judgment Format

Several studies have assessed the validity of different psychometric scales employed to measure subjective risk judgments for combined hazards (e.g., Hampson et al. 2003; French et al. 2002, 2004, 2006). These assessments have typically been made via two approaches: First, the risk judgments obtained by the metric(s) are compared to anticipated results. For example, Hampson et al. (2003) predicted that the synergistic risk attributable to drinking-and-driving would be familiar to most people, and that a metric which obtained risk judgments reflecting knowledge of this synergy could be considered valid. Second, multiple metrics are employed, and the risk judgments obtained by each metric are compared; agreement between these judgments is interpreted as an indicator of validity. However, two distinct problems have emerged with this latter approach. First, there have been instances where two scales demonstrate agreement in one comparative study (indicating validity), but do not demonstrate agreement in another (see French et al., 2002, and French et al., 2006). Second, where disagreement between different metrics is identified, there is no 'gold standard' measure to which the results obtained from either metric can be compared for validation purposes. Consequently, in making our assessment of the validity of the composed-task format, we adopted the former approach and compared the results we obtained to predicted results. This approach can be described as an assessment of *criterion-related validity* (Litwin, 2003), and we adopted this method because it avoids the complexities, as described above, of assessing validity via comparisons between multiple metrics. Our predictions, which are specific to each hazard combination, are now discussed.

The two studies presented in this paper featured either one or all of the following three hazard combinations which have been found, in practice, to present synergistic risks: alcohol-driving (Cherpitel, Tam, Midanik, Caetano, & Greenfield, 1995; Institute for

Alcohol Studies, 2010; Office for National Statistics, 2009), aspirin-clopidogrel (Delaney, Opatrny, Brophy & Suiss, 2007; Hallas et al., 2006), and radon-tobacco (Barros-Dios et al., 2002; Darby et al., 2005; Pershagen et al., 1994).[9] We predicted that a majority of lay participants would correctly judge that the alcohol-driving combination presents a synergistic risk of suffering a fatal accident. We made this prediction as many people probably understand, whether via direct or vicarious experience of each hazard, that a serious accident is much more likely if the driver has a severely impaired ability to concentrate, judge distances, react quickly, coordinate his/hers bodily movements, etc. By contrast, we predicted that a majority of our lay participants would not be aware that the aspirin-clopidogrel combination presents a synergistic risk of gastro-intestinal bleeding, because the combination is probably not familiar to most individuals and, consequently, it is unlikely they would know much/anything about whether combining these two drugs results in particular risks or benefits. The third hazard combination we presented to our lay participants is radon-tobacco, which presents a synergistic risk of developing lung cancer. We decided that there would be little reason to believe the underlying mechanism for this particular synergistic risk would be understood by the participants, as the mechanistic process is complex and not yet fully understood by scientists (Harley, Chittaporn, Heikkinen, Meyers & Robbins, 2008). However, authors of both a US- and UK-based studies, each employing a different metric, reported that

[9] We could not identify a study that autonomously confirmed/denied that the likelihood of having a fatal accident for someone who drives a vehicle whilst intoxicated by alcohol was greater than the sum of the likelihood of a fatal accident for someone who does either of these two activities alone. However, we considered the risk attributable to alcohol-driving to be synergistic. This is because evidence from the Institute for Alcohol Studies (2010) indicates that the annual risk of a fatal accident for a person who becomes intoxicated by alcohol on an average number of occasions is 1 in 100,000. In addition, evidence from the Office for National Statistics (2009) shows that the annual risk of a fatal accident for a person who drives a vehicle on a road, an average number of occasions, is 3 in 100,000. Moreover, Cherpitel et al. (1995) report that the risk of a fatal accident increases 11-fold for a person who drives whilst intoxicated, thus, making the risk of a fatal accident for someone who drives a vehicle whilst intoxicated to be approximately 33 in 100,000; this is greater than the sum of the risk attributable to each constituent hazard in isolation.

participants judged the risk attributable to the radon-tobacco combination as synergistic (Eiser, Reicher & Podpadec, 1995; Hampson et al., 2000). In line with these findings, we also predicted that a majority of our participants would attribute a synergistic risk model to the combination of radon-tobacco. Hence, results consistent with our three predictions would provide evidence of criterion-validity for the composed format.

3.1.4. Framing and the Face Validity of the Composed Risk Judgment Format

Studies show that subjective risk judgments can change as a result of how a decision problem is described, or 'framed' (see Levin, Schneider & Gaeth, 1998; Wang, 1996). More specifically, whether risk in a decision task is described in verbal or numerical terms can affect subjective risk estimates based on that information (Capriotti & Waldrup, 2005; Vahabi, 2010). For example, in two separate studies, Knapp and colleagues (Knapp, Gardner, Carrigan & Raynor, 2009; Knapp, Raynor, & Berry, 2004) found that verbal descriptions concerning the probability of medication side-effects led to significantly higher risk magnitude estimates than numeric descriptions. Furthermore, studies conducted by Windschitl and Wells (1996) indicate that judgment tasks, which require individuals to conceptualize uncertainty in a numeric form, tend to evoke deliberative-rule based thinking, whereas verbal conceptualizations promote more intuitive and associative thinking. Hence, in the context of a judgment task that involves estimating the risk for a combined hazard, one could reasonably expect individuals to respond differently if the task is presented in a verbal or numeric frame. For instance, a numeric frame might make a formal, mathematical approach more salient for respondents, which could, for example, lead them to employ an additive model of risk consistent with the notion of adding two hazards together. By contrast, verbal framing could promote more conceptual and associative thinking, which may, in turn, influence the respondent to consider whether the mechanistic interaction of two hazards may influence the overall risk in a synergistic or antagonistic direction. Hence, the extant evidence indicates these two frames could influence subjective risk judgments for combined hazards.

In the two studies presented in this paper, each participant made a risk judgment for a combined hazard using a composed task format presented in either a verbal or numeric frame. If participants' responses differed according to the frame, this would suggest that a judgment obtained using the composed format was dependent on the description of the task at hand. Consequently, the data obtained could be deemed to be low in face validity, as the translation of the construct (i.e., risk judgments) would vary according to subtle changes in task description. However, we predicted that our participants' risk model judgments (i.e., sub-additive, additive, or synergistic) would not differ according to the two frames. We made this prediction as the 'composed format' aims to focus the participants' attention on the need to express their beliefs concerning the risk *model*, rather than risk *magnitude* (which can vary according to a numeric or verbal frame), attributable to the combination.

3.1.5. Assessing the Discriminant Validity of the Composed Risk Judgment Format

Several studies have found that prior judgmental experience in the task domain can improve the veridicality of risk-related judgments (Johnson & Bruce, 2001; Murphy & Brown, 1984; Thomson, Onkal, Avcioglu & Goodwin, 2004). Therefore, it seems reasonable to assert that certain individuals, as a result of domain-specific experience, may have a better understanding the risk attributable to certain hazard combinations. For example, individuals who are independently responsible for prescribing drugs (i.e., Independent Prescribers, such as doctors and pharmacists; referred to hereafter as 'IPs') are likely to have a better understanding of the risks associated with combining specific medications compared to individuals without the same experience and/or pharmacology-related qualifications. Thus, assuming significant differences existed between two groups concerning their risk model judgments for a specific hazard combination, it would be important to identify this difference in empirical research in which the two groups provided risk judgments for that combination. Without being able to discriminate between the differences in the two groups' judgments, it would not be possible to identify whether one groups' judgments were inconsistent with 'objective' risk data and, therefore, whether any action should be taken to remedy the situation. Hence, it is vital that any method employed to assess subjective risk judgments for combined hazards possesses discriminant validity (Laver-Fawcett, 2007). To assess the discriminant validity of the composed task format, we conducted a study in which both IPs and non-IPs provide risk judgments for the aspirin-clopidogrel combination. We predicted that the synergistic risk attributable to this combination will be known to the IPs, but not to the non-IPs, and that this will be reflected in risk judgments obtained using the composed format.

3.1.6. Summary of Present Research

In two studies, we employed a composed task format to assess subjective risk judgments for combined hazards. In Study 1, participants provided risk judgments for one of three hazard combinations: alcohol-driving, aspirin-clopidogrel, and radon-tobacco, and the design of this study enabled us to assess the criterion and face validity of the composed format. In Study 2, both non-experts and domain-experts (IPs) made risk judgments for the aspirin-clopidogrel combination. This study enabled us to assess whether the composed format can discriminate (i.e., discriminant validity) between the risk judgments of different populations. Furthermore, we present epistemological interpretations of the results from both studies in order to provide important insights into the reasons individuals may, or may not, make veridical judgments of synergistic risks.

3.2. Study 1

3.2.1. Method

3.2.1.1. Participants

One-hundred-and-six participants (49 men, 56 women and 1 who did not indicate his/her gender) aged 18 to 75 (M = 35.79, SD = 17.69) were recruited online via five websites dedicated to the coverage of social science research. Forty-three percent of participants were resident in the US, 40% were resident in the UK, and the remaining 17% of participants were resident in one of nine other Asian, Australasian, European or North American countries. Twenty-eight percent had completed a secondary/high school education, 27% had completed some postsecondary schooling, and 44% had a university education.

3.2.1.2. Design

The experiment followed a 3 (hazard combination: alcohol-driving, radon-tobacco, aspirin-clopidogrel) x 2 (frame: numerical, verbal) design, with both factors as between-subjects. The dependent variable was the subjective risk model attributable to the hazard combination (risk model: sub-additive, additive, or synergistic).

3.2.1.3. Materials

The judgment task presented to each participant initially featured a short paragraph, comprised of two sentences, which participants were asked to read (see Appendix Three). The first sentence stated that research evidence showed that the likelihood of an adverse outcome (e.g., gastro-intestinal bleeding) increased for an individual exposed to a specific single hazard (e.g., taking aspirin). The second sentence stated that research evidence showed the likelihood of that same adverse outcome (e.g., gastro-intestinal bleeding) also increased for an individual exposed to a different single hazard (e.g., taking the drug 'clopidogrel'). The wording employed in these two sentences was manipulated so that participants either read two sentences that described the likelihood of the adverse outcome in either a 'verbal' frame or a 'numeric' frame. Specifically, participants in the verbal condition read sentences that described the likelihood as "*an increased chance*" for each hazard. Whereas, participants in the numeric condition read sentences that described the likelihood for each hazard in the form of a natural frequency which had been derived from empirical research data (e.g., "*a 1 in 100,000 chance*"). Hence, participants in the verbal condition, unlike those in the numeric condition, were not provided with the 'objective' risk magnitude and, therefore, made their own subjective assessment of the risk attributable to each constituent hazard. All natural frequencies (see Table 7) reported in the numeric condition featured the same denominator to avoid the introduction of an unwanted framing effect (see Lipkus, 2007; Peters, 2008).

Table 7. Natural frequencies, as described in each 'numeric frame' judgment task, of adverse outcomes following exposure to/use of a specific hazard (frequencies calculated from data source shown).

Hazard Combination in Judgment Task	*Constituent Hazard*	*Adverse Outcome*	*Natural Frequency of Adverse Outcome*	*Data Source(s)*
Alcohol – Driving	*Alcohol*: becoming intoxicated by alcohol an average number of times per year	Fatal accident in any given year	1 in 100,000	Institute for Alcohol Studies (2010)
	Driving: driving vehicle on a road an average number of times per year	Fatal accident in any given year	3 in 100,000	Office for National Statistics (2009)
Aspirin - Clopidogrel	*Aspirin*: taking a low dose each day	Gastro-intestinal bleeding in any given year	100 in 100,000	Hallas et al. (2006)
	Clopidogrel: taking a low does each day	Gastro-intestinal bleeding in any given year	10 in 100,000	Hallas et al. (2006)
Radon – Tobacco	*Radon*: living in a dwelling where there is a high level of radon	Lung cancer during lifetime	4,000 in 100,000	Reif & Heeren (1999)
	Tobacco: smoking 20 cigarettes per day throughout adulthood	Lung cancer during lifetime	17,000 in 100,000	Villeneuve & Mao (1994)

After the first paragraph, participants were then instructed to consider the likelihood of an individual experiencing the adverse outcome, as mentioned in the first paragraph (e.g., gastro-intestinal bleeding), when exposed to both hazards (e.g., aspirin *and* clopidogrel). Participants were asked to state, using a multiple-choice response format, whether they judged this likelihood to be "*less than*", "*equal to*", or "*more than*" the likelihood for an individual exposed to only the first hazard (e.g., aspirin) "*added to*" the likelihood for an individual exposed to only the second hazard (e.g., clopidogrel). The layout, style, and content of the judgment task were developed in accordance with guidelines outlined by Osterlind (1998) for the construction of multiple-choice response items.

Having completed the judgment task, participants then read the following instruction "*Please indicate how confident you are that your judgment (i.e., less than, equal to, or more than) in the previous task represents what has been found in scientific research, where: 0% = "I have no idea whether my judgment represents what has been found in scientific research" and 100% = "I am certain my judgment represents what has been found in scientific research"*." To respond to this question, participants could select one of eleven categorical options distributed in ten percent intervals (i.e., 0%, 10%, 20% … 100%).

3.2.1.4. Procedure

Each participant was presented with the experimental materials via an online survey system. The system randomly allocated participants to receive a judgment task concerning either the alcohol-driving, radon-tobacco, or aspirin-clopidogrel combinations. The system also randomly allocated participants to receive the judgment task in either the numerical or verbal frame. Each 'hazard combination group' consisted of 17 or 18 participants who received the task in a verbal frame, and 17 or 18 who received the same task in the numeric frame. Participants were advised that they had an unlimited time to participate in the study (*M* = 10 minutes 28 seconds), to complete the questions in a place where they would not be distracted, and not to consult any materials or persons whilst participating.

3.2.1.5. Statistical Analysis

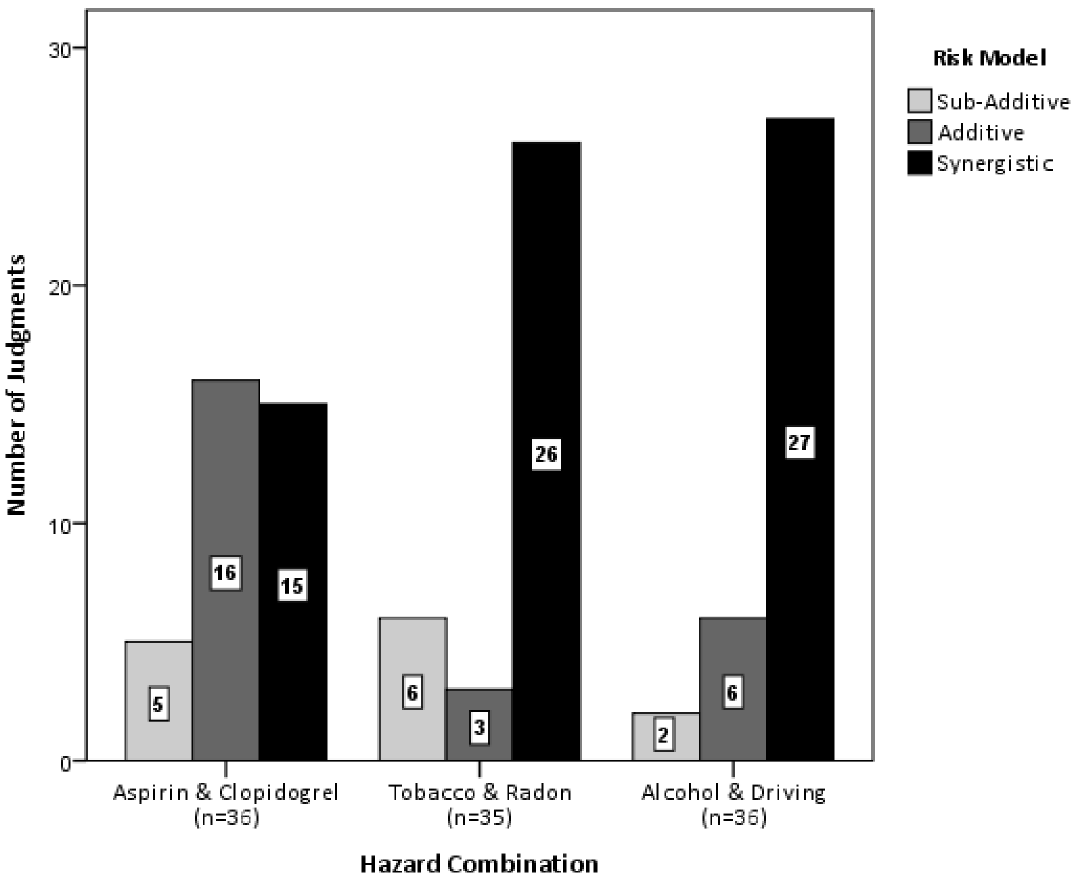
The dependent and independent variables in Study 1 were, primarily, categorical variables. In order to test for main effects and interactions between these variables, we analysed the data using hierarchical loglinear analysis. Significant interactions were further analysed using chi-square (χ^2) tests. The data concerning the extent to which each participant believed his/hers risk judgment was veridical was treated as a continuous variable, and was analysed using ANOVAs.

3.2.2. Results

3.2.2.1. Risk Judgments

Categorical risk judgments for each of the three hazard combinations are displayed in Figure 3. Before we performed the hierarchical loglinear analyses, we assessed whether the data met the test assumption that no less than 20% of the data cells should have expected frequencies less than 5 (Field, 2009). However, because few participants judged the risk attributable to the combined hazards as 'sub-additive', the data did not meet this assumption for three-way analyses (77% of cells featuring expected frequencies less that 5). Consequently, we collapsed the 'additive' and 'sub-additive' categories into one category, which resulted in two categories for the risk model variable (i.e., 'synergistic' and 'non-synergistic'). Collapsing categories in this way is common in research that employs hierarchical loglinear analysis (e.g., Chung, 1996; Fairclough, Boddy, Hackett & Stratton, 2009), and is appropriate in circumstances, such as those here, where the research objectives (i.e. investigating whether or not participants judged the risk attributable to the hazard combinations as a synergistic risk) are not impeded (Field, 2009). Collapsing the categories resulted in data that met the test assumptions and made the three-way analysis viable.[10]

Figure 3. Study 1: Judgments of the risk model attributable to each hazard combination (N = 106)



[10] Hierarchical loglinear analyses identified that participants' risk judgments in both Studies 1 and 2 did not differ significantly according to gender, χ^2s (2) <= 2.32, *p*s > 0.05, or age, χ^2s (2) <= 3.58, *p*s > 0.05. Hence, these variables did not form part of the subsequent data analysis.

3.2.2.2. Risk Judgments, Hazard Combination, and Framing

To assess whether participants' judgments varied according to hazard combination and/or task frame, we performed a three-way hierarchical loglinear analysis: risk model x hazard combination x frame. This identified a significant main effect for risk model, χ^2 (1) = 8.61, $p < 0.01$, that was qualified by significant two-way interaction between the hazard combination and risk model, χ^2 (2) = 11.91, $p < 0.01$. The main effect for risk model was attributable to the greater proportion of hazard combinations, overall, that were judged to present a synergistic risk (64%) rather than a non-synergistic risk (36%), χ^2 (1) = 8.49, $p < 0.01$. The two-way interaction between hazard combination and risk model was investigated via separate analysis of participants' risk judgments for each hazard combination. This revealed that a significantly greater proportion of participants (77%) judged that the alcohol-driving combination would present a synergistic (cf. non-synergistic) risk, χ^2 (1) = 10.31, $p < 0.001$. Similarly, 74% of participants in the radon-tobacco group judged that the combination would present a synergistic (cf. non-synergistic) risk, χ^2 (1) = 8.26, $p < 0.01$. However, there was no significant difference between the proportion of participants who judged that the aspirin-clopidogrel combination would present a synergistic (42%) and a non-synergistic risk (58%), χ^2 (1) = 1.00, $p > 0.05$. No other significant interactions or main effects were found, χ^2s (1) <= 0.73, ps > 0.05. Hence, the results show that participants' risk judgments did not differ significantly whether they were presented with the judgment task in a numeric or verbal frame, and this was the case irrespective of the hazard combination under consideration.

3.2.2.3. Confidence in Veridicality of Risk Judgments

A 3 (hazard combination) x 2 (frame) independent measures ANOVA was performed on the veridicality judgment data. This identified that the difference in veridicality judgments between the aspirin-clopidogrel (M = 53.61, SD = 29.19), radon-tobacco (M = 61.14, SD = 32.88) and alcohol-driving (M = 67.35, SD = 29.57) groups was not significant, $F(2, 99) = 1.72$, $p > 0.05$. Furthermore, the difference in veridicality judgments between the numeric (M = 61.92, SD = 31.00) and verbal (M = 59.25, SD = 30.88) frame conditions were also non-significant, $F(1, 99) = 0.19$, $p > 0.05$. Although a significant interaction was identified between hazard combination and frame, $F(2, 99) = 4.97$, $p < 0.01$, simple effects tests (employing a Bonferroni correction for multiple comparisons) for each hazard combination indicated that the differences between judgments in each framing condition were not significant, $ts(18) <= 2.36$; $ps > 0.05$. More specifically, for the aspirin-clopidogrel combination, judgments in the numeric frame condition (M = 62.22, SD = 24.15) were higher than in the verbal frame condition (M = 45.00, SD = 31.86); similarly, for the radon-tobacco combination, judgments were higher in the numeric condition (M = 67.78, SD = 31.54) than the verbal condition (M = 54.12, SD = 33.74); however, for the alcohol-driving combination judgments were lower in the numeric condition (M = 55.00, SD = 37.24) than the verbal condition (M = 78.33, SD = 14.25).[11]

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[11] Individuals with lower (cf. higher) levels of numeracy are less able to comprehend and process numeric risk-related information (Peters, 2008; Reyna & Brainerd, 2007; Schwartz, Woloshin, Black & Welch, 1997). Hence, to assess whether numeracy affected participants' responses using the composed format, all participants in both our studies answered eight numeracy questions developed by Lipkus, Samsa and Rimer (2001). In Studies 1 and 2 the mean numeracy score was 7.08 (SD = 1.19; Md = 7) and 7.41 (SD = 1.01; Md = 8), respectively. Using a median-split, we classified all participants who answered all eight questions correctly as 'more numerate', and those with seven or fewer correct as 'less numerate' (48.1% of participants in Study 1, and 64% in Study 2, were classified as more numerate). A series of separate hierarchical loglinear analyses for Studies 1 and 2 revealed no significant main effects or interactions featuring the numeracy variable (χ^2s (2) <= 2.29, ps > 0.05). This suggests the composed format may provide a valid means of assessing subjective risk judgments for combined hazards amongst both more and less numerate individuals (i.e., the format has external validity). However, this is a tentative conclusion, as

3.2.3. Discussion

A majority of participants in Study 1 judged that the alcohol-driving and radon-tobacco combinations, but not the aspirin-clopidogrel combination, present a synergistic risk. These findings are consistent with our predictions and, therefore, suggest that the composed task format we employed possesses criterion-related validity. In addition, participant' risk judgments did not differ as a result of manipulations in the context information (i.e., framing) which preceded the judgment task. This offers some evidence towards the format's face validity, as the translation of the risk model construct did not vary according to the task frame. In other words, the composed format accurately translates the risk model construct.

In attempting to understand the results of Study 1 from an epistemological perspective, one potential interpretation is that the extent to which each hazard combination has been highlighted as a 'dangerous combination' in public domains (e.g., by media sources, public authorities, etc.) is reflected in the participants' risk model judgments. In other words, it could be suggested that participants specifically judged that the alcohol-driving and radon-tobacco combinations would present synergistic risks because they had previously been made aware of the risk attributable to these two combinations. However, this interpretation seems unlikely because participants were no more/less confident in the veridicality of their judgments for either of the three hazard combinations. That is, participants who, for example, made risk judgments for the alcohol-driving combination, were no more confident that their subjective judgments were consistent with objective risk assessments than participants who, for example,

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we acknowledge that many participants who were classified as 'less numerate' answered seven questions correctly which, therefore, indicates our samples primarily consisted of individuals with relatively high numeracy skills.

made judgments for the much less familiar aspirin-clopidogrel combination. This indicates that familiarity with data concerning the combination's objective risk was not a key factor determining participants' risk model judgments, and that risk judgments for all combinations were equally based on subjective estimations.

We would argue that the synergistic risk attributable to the alcohol-driving combination is recognized by most individuals because, as indicated above, it is relatively easy to appreciate that a person who is intoxicated is less able to control a vehicle. In other words, people can readily formulate a mental model of the mechanism underlying the harmful synergy. However, this interpretation of the 'comprehension of synergistic risk' does not appear to generalize to the radon-tobacco combination which, like alcohol-driving, was also judged to present a synergistic risk by most participants. That is, it is unlikely that participants understood the bio-chemical mechanism underlying the harmful synergy between smoking and radon, as this is something not yet fully understood by scientists (Harley et al., 2008). An alternative interpretation of participants' judgments for the radon-tobacco combination is that many participants simply concluded that the harmful health-related effects of each of the two hazards would be substantially enhanced by combined exposure. Such an intuitive understanding of synergistic risk seems plausible, and offers a partial explanation for other evidence indicating that individuals may hold synergistic models of risk for the radon-tobacco combination (Eiser et al., 1995; Hampson et al., 2000). This interpretation then raises the question as to why a majority of participants did not employ this intuitive synergistic risk model when making a judgment for the aspirin-clopidogrel combination. We suggest, as indicated above, that it is likely that most individuals know very little about the risk and/or benefits of combining aspirin and clopidogrel, and that this leads to greater epistemic uncertainty regarding the appropriate risk model for this combination. Research shows that lay people tend to perceive medicinal drugs as beneficial (Kraus, Malmfors & Slovic, 1992), and that subjective judgments' of risks and benefits are often confounded in individuals' minds (Alhakami & Slovic, 1994). Consequently, it is possible that many of our participants believed that the overall risk for the aspirin-clopidogrel combination may be attenuated by the potential benefits. The results of Study 1, which show that the highest number of judgments that the risk was non-synergistic was observed in the aspirin-clopidogrel condition, provide some evidence in support of this thesis.

If epistemic uncertainty concerning the risk/benefits of the aspirin-clopidogrel combination was a factor that influenced participants' judgments in Study 1, then one might expect that IPs would possess the necessary knowledge to understand that a synergistic risk is attributable to this combination. Similarly, one might also expect IPs to be more confident in the extent to which his/her risk judgments for the combination were veridical. To investigate these predictions, we conducted a second study in which a group of IPs and a group of lay individuals were asked to judge whether the risk attributable to the combination of aspirin-clopidogrel was less than, equal to, or more than the sum of the risk for each of the constituent drugs. Importantly, the data obtained in this study would also facilitate an assessment of the discriminant validity of the composed task format. That is, a significant difference between the responses of the two groups would provide evidence of the formats capacity to distinguish between different risk model judgments for different populations (Laver-Fawcett, 2007).

3.3. Study 2

3.3.1. Method

3.3.1.1. Participants

To recruit a sample of domain-experts (IPs), and a sample of non-experts matched to the IPs on key socio-demographics (i.e., age, gender, education, and national residence), we employed chain-referral sampling (Penrod, Preston, Cain & Starks, 2003). We initially made contact with individuals (known as 'gatekeepers') who, by virtue of their employment, were in a position to recruit other individuals that met the socio-demographic profile suitable for participation in the study (Penrod et al., 2003). Several gatekeepers were employed in the recruitment of both IPs and non-experts to minimize selection bias (Atkinson & Flint, 2003), and the gatekeepers did not participate in the study.

The sample of IPs (*n* = 31) were recruited by five gatekeepers, who either participated in a university alumni network, mediated an online forum for pharmacists, or chaired a professional association for UK pharmacists. The recruited participants consisted of 17 men and 13 women (one participant's gender not stated), and their ages ranged from 28 to 59 years (*M* = 42.40, *SD* = 9.97). We established, via a questionnaire, that the 31 participants met all of the following criteria: resided in the UK, had qualified to independently prescribe prescription-only drugs, were employed in a role where they independently prescribed drugs, and considered the potential for adverse drug-drug interactions at least once per week in their professional role.

Our sample of non-experts (*n* = 30) were recruited by six gatekeepers from a range of UK-based public and private sector organizations. The sample of participants held a variety of professional positions that included Head Teacher, Project Manager, Financial Analyst, Administrator, and Chartered Accountant. The non-expert participants were matched to the IPs in terms of being UK residents, aged between 26 and 64 (M = 39.73, SD = 10.14), and educated to Bachelor's Degree level or higher. Consistent with the IP group, the non-expert group consisted of 14 men and 16 women. There was no significant difference between the mean age of the IP and non-expert groups, $t(58) = 1.03$, $p > 0.05$, and there was no significant difference between the proportion of men/women in the two groups, χ^2 (1) = 0.60, $p > 0.05$. Questionnaire-elicited data was obtained from the non-expert participants to ensure none of them met the criteria for inclusion in the IP group (see above).

3.3.1.2. Design

The experiment followed a 2 (domain expertise: IP, non-expert) x 2 (frame: numerical, verbal) design with both factors as between-subjects. The dependent variable was the subjective risk model attributable to the hazard combination (risk model: sub-additive, additive, or synergistic).

3.3.1.3. Materials

The design of the judgment task materials presented to each participant replicated that employed in Study 1. In Study 2, only the aspirin-clopidogrel judgment task was presented to participants. After completing the task, participants provided veridicality judgments as per Study 1. In addition, participants in Study 2 were asked to state whether, prior to participation in the study, they were aware that (a) use of aspirin increases the risk of gastro-intestinal bleeding, and (b) use of clopidogrel increases the risk of gastro-intestinal bleeding.

3.3.1.4. Procedure

The experimental materials were presented to all participants via an online survey system. The system randomly allocated the judgment task in either the numerical or verbal frame within both the non-expert and IP groups. Participants received the same instructions provided in Study 1. The mean participation time was 10 minutes 47 seconds.

3.3.1.5. Statistical Analysis

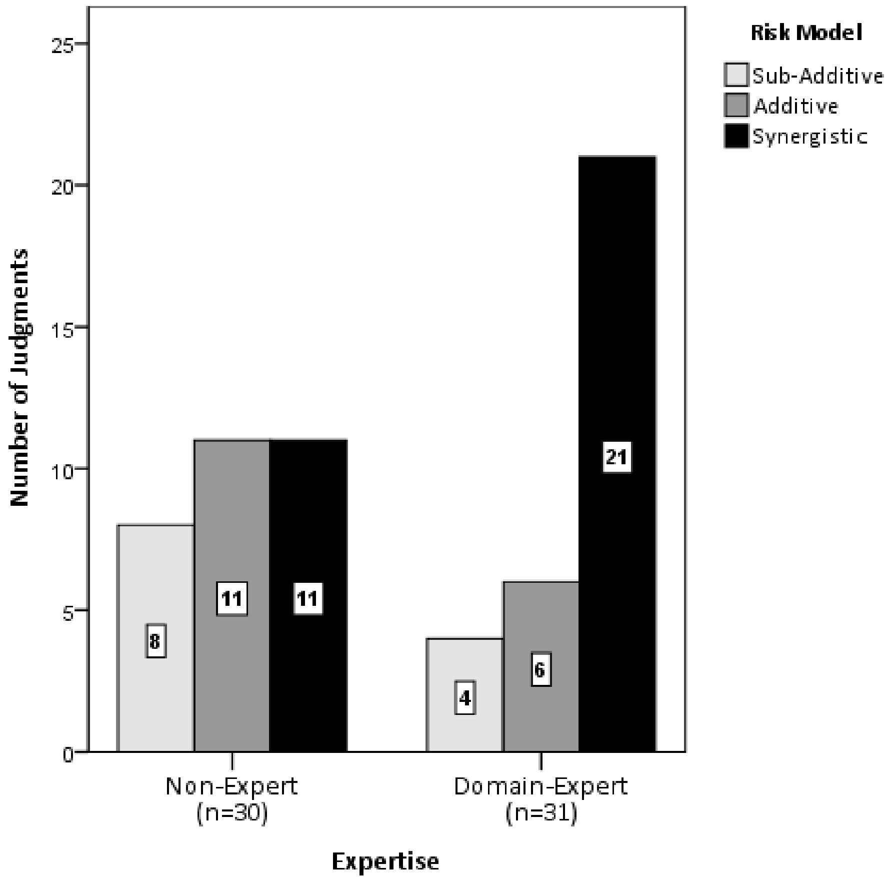
Data analysis was performed as per Study 1. As observed in Study 1, the proportion of cells with an expected count of 5 or more was not sufficient to meet the assumption for a three-way hierarchical loglinear analysis. To overcome this issue, we collapsed the 'additive' and 'sub-additive' categories into one category (i.e., 'non-synergistic'). This resulted in data that met the test assumptions, making the three-way analysis viable.

3.3.2. Results

3.3.2.1. Risk Judgments

Categorical risk judgments for both the non-expert and IP groups are displayed in Figure 4. In the following analysis, the 'additive' and 'sub-additive' categories were collapsed into one category.

Figure 4. Study 2: Domain-experts' and non-experts' judgments of the risk model attributable to the aspirin-clopidogrel drug combination (N = 61).



3.3.2.2. Risk Judgments, Expertise, and Framing

To assess whether participants' risk judgments varied according to expertise and/or task frame, we performed a three-way hierarchical loglinear analysis: risk model x domain expertise x frame. This identified a significant two-way interaction between expertise and risk model, χ^2 (1) = 5.99, $p < 0.05$. No other significant interactions or main effects were found, χ^2s (1) <= 0.41, *p*s > 0.05. Hence, participants' risk judgments did not differ significantly between the numeric or verbal frame conditions and this was the case across both the IP and non-expert groups.

The two-way interaction between expertise and risk model was investigated via separate analysis of risk judgments for each expertise group. This revealed that a significantly greater proportion of IPs judged that the aspirin-clopidogrel combination would present a synergistic (68%), rather than non-synergistic, risk, χ^2 (1) = 3.90, $p < 0.05$. However, there was no significant difference between the proportion of non-experts who judged that this combination would present a synergistic risk (37%) and those who judged that the combination would not, χ^2 (1) = 2.13, $p > 0.05$.

3.3.2.3. Confidence in Veridicality of Risk Judgments

A 2 (domain expertise) x 2 (frame) independent measures ANOVA was performed on the veridicality judgment data. This identified a significant main effect for expertise, $F(2, 57) = 3.14$, $p = 0.04$ (employing a lopsided test of significance; Abelson, 1995; Levine & Banas, 2002), with IPs' being significantly more confident ($M = 57.10$, $SD = 32.48$) than non-experts' judgments ($M = 42.67$, $SD = 30.00$) regarding the extent to which their risk model judgments were veridical. However, no other significant main effects or interactions were identified, Fs(1, 57) => 0.48, ps < 0.05.

3.3.2.4. Prior Knowledge of Constituent Hazards and their Associated Risk

We asked all participants whether, prior to participation in the study, he/she was aware that separate use of either aspirin *or* clopidogrel increases the risk of gastro-intestinal bleeding. Ninety-four-percent of IPs reported that they were aware of this potential side-effect for separate use of both drugs. By contrast, only ten percent of non-experts reported being aware of this side-effect for separate use of both drugs.

3.3.3. Discussion

As in Study 1, the results of Study 2 revealed no effect for the verbal/numeric framing manipulations, and identified risk model judgments consistent with our prediction for non-expert judges; providing further evidence that the composed format provides a valid means of assessing risk judgments for combined hazards. Importantly, Study 2 demonstrated that the format can help to distinguish between different response patterns for groups of individuals whom one might expect to respond differently to the judgment task; thus, providing evidence of the format's discriminant validity. Furthermore, the similarity between the judgment pattern observed for the aspirin-clopidogrel combination in Study 1 and for the non-experts in Study 2 provides some evidence of the format's reliability.

Previous examinations of the risk judgments of experts indicate that experts are more likely to show "good" judgmental performance when the *ecological validity* (i.e., the degree to which the expert makes a judgment within their professional domain) and the *learnability* (i.e., the degree to which the experts judgmental veridicality has been improved by the availability of objective data or usable feedback) of the judgment task are high (Bolger & Wright, 1994; Rowe & Wright, 2001; Thomson et al., 2004). Evidence that the judgment task employed in Study 2 was more ecologically valid for the IPs was evident in that this group of participants (a) were much more aware of the side-effects attributable to both aspirin and clopidogrel when taken independently, and (b) regularly considered the effects of drug-drug interactions in their work role. The results also suggest that learnability probably played a role in the IPs' risk model judgments, because this group of participants were more confident that their judgments were consistent with objective risk assessments for the aspirin-clopidogrel combination. Hence, the judgment task presented to participants in Study 2 appears to have been one that was higher in ecological validity and learnability for participants in the IP group. It, therefore, seems reasonable to assert that these two factors played a role in the judgments made by the IPs in Study 2, who demonstrated greater veridicality (cf. non-experts) in their risk judgments for the hazard combination of aspirin-clopidogrel.

3.4. General Discussion

Like the composed format employed in our studies, other metrics designed to assess subjective risk judgments for combined hazards also explicitly require participants to provide relative, rather than absolute, risk estimates (e.g., Eiser et al. 1995; Hampson et al. 2000). However, these metrics require participants to make their judgments relative to a risk that takes the form of familiar exemplar (e.g., judging the risk for drinking-driving relative to the risk of smoking one pack of cigarettes per day; Hampson et al., 2000). This approach does not explicitly require respondents to estimate the risk for the combined hazard relative to the risk attributable to both hazards that constitute the combination. Therefore, the task may be framed in such a manner that it is not clear to the respondent that their judgment/response should reflect their beliefs concerning the *risk model* attributable to the combination (Goodwin & Wright, 2010; Wright et al., 2009). By explicitly requiring respondents to make their judgments relative to the constituent risks, as per the composed format, researchers can be more confident that respondents' judgments reflect whether they believe the combination presents a risk that is less than, equal to, or greater than, the sum of the risk attributable to each constituent hazard.

The data we obtained in both our studies reflects participants' risk *model* judgments, and not specific risk *magnitude* estimates. Hence, one could argue that even where a person judge's that a combination presents a synergistic risk, he/she may still not have an accurate understanding of the combination's specific risk magnitude (as synergistic risks can vary in magnitude). However, we suggest that it may be too much to expect most non-experts to make accurate estimates of synergistic risk magnitudes, because this is a complex task requiring an understanding of the way such magnitudes vary in relation to the intensity, duration, proximity and frequency of exposure to each constituent hazard (Berenbaum, 1989; Cogliano, 1997). Although Bonnin-Scaon, Lafon, Chasseigne, Mullet and Sorum (2002) have demonstrated that it is possible to teach individuals specific synergistic risk magnitudes in relation to different consumption levels of alcohol and tobacco, the teaching procedure they employed lasted 60-90 minutes and involved a complex series of one-to-one training sessions. Their study serves to illustrate the complexity of acquiring precise knowledge of synergistic risk magnitudes, and indicates that the teaching of such precise magnitudes may only be feasible where time and resources are plentiful. Therefore, in terms of bringing certain synergistic risks to the attention of large populations, we argue that it is more important that people understand that a combination presents a synergistic risk, than it is for people to appreciate the exact extent to which the combined risk exceeds the sum of the constituent risks (for a similar assertion see Hampson et al., 2003, p.1029). Hence, from this pragmatic perspective, it is more important that researchers can make valid assessments of subjective risk model, rather than risk magnitude, judgments for combined hazards.

A further argument in favour of assessing subjective risk models (cf. risk magnitudes) for combined hazards is that people often have difficulty in accurately representing their perceptions of risk magnitudes in numerical/linear formats (Borland, 1997; Fischhoff & Bruine de Bruin, 1999; Windschitl, 2000). Evidence suggests that respondents often use or interpret estimation metrics in a way not intended by the researcher, and that single-point risk estimates may not necessarily reflect an individual's more intuitive understanding of risk and uncertainty (Borland, 1997; Wallsten, Budescu & Zwick, 1993; Windschitl, 2002; Windschitl & Wells, 1996). Thus, we argue that the composed format employed in our studies places less onus on the respondent to be numerically-specific when providing a risk estimate, whilst allowing them to express a conceptual understanding of the directional effects, in terms of a risk model, of combining two specific hazards. The composed approach may, therefore, be more suited to enabling individuals to express an understanding of synergistic risk, even when that understanding is more tacitly, than numerically, encoded.

The results of Study 1 showed that many lay individuals can/do make veridical risk judgments for hazard combinations that have been found, in practice, to present synergistic risks. However, it is of concern that we also found that this veridicality does not extend to all such combinations (i.e., aspirin-clopidogrel). Reassuringly, the greater proportion of veridical risk model judgments made by the domain-experts in Study 2 indicates that knowledge of the synergistic risk attributable to certain combinations can be learned. Importantly, this suggests that laypersons should also be able to acquire a more veridical understanding of the synergistic risk attributable to certain hazard combinations, provided they are exposed to effective risk communications and/or learning opportunities. However, the flip-side of our findings from Study 2 is that nearly a third of the IPs did not demonstrate an awareness of the synergistic risk attributable to the aspirin-clopidogrel combination. This indicates that improving the accuracy of such risk judgments amongst IPs should lead to improvements in patient care where poly-pharmacy is applied.

In interpreting the results of Studies 1 and 2, we identify a number of different reasons that could explain why certain synergistic risks are understood by people. In the case of alcohol-driving, it is possible that individuals can readily formulate a mental model of the mechanism underlying the undesirable synergy. Alternatively, as in the case of radon-tobacco, it may simply be that the threat of both hazards when combined may be perceived as substantially more potent than the sum of the constituent threats (i.e., something akin to a 'synergistic risk heuristic' may be employed in the risk judgment process). By contrast, in the case of other hazard combinations (e.g., aspirin-clopidogrel), it may be that specialist domain-specific knowledge and/or experience is necessary to understand whether an interaction between the hazards serves to increase, decrease, or have no effect on the risk attributable to the constituent hazards. Taken together, these interpretations indicate that risk communications concerning synergistic risks may be most effective if the message content provides information that (a) details the mechanism underlying the synergy, (b) explains that the combined risk is greater than the sum of the constituent risks, and/or (c) encourages the recipient, in a more general sense, to become more practiced at considering the potential for harmful interactions between hazards. However, care should be taken not to encourage individuals to assume a synergistic risk model for all hazard combinations as this could lead to non-veridical risk judgments for certain combinations.

3.4.1. Limitations and future Directions

There are some limitations to the present research which provide useful opportunities for future studies. First, we only assessed risk judgments for synergistic risk combinations and therefore, have not evaluated the extent to which individual's judgments for sub-additive or additive risk combinations are veridical. Second, our comparison of non-expert and domain-expert judgments focused on only one drug-drug combination and, consequently, the differences identified in the study may or may not be evident for judgments of other drug combinations. Finally, the extent of the validity and reliability of the composed format may only be firmly established via a greater number and variety of applications. Hence, we would encourage future studies to use the composed format to assess risk model judgments for a wide range of sub-additive, additive and synergistic risk combinations, in relation to a variety of hazard domains (e.g., health, ecological, social, etc.), and with respondents of varying degrees of domain expertise.

3.5. Conclusion

The accumulation of evidence showing that various hazard combinations present synergistic health risks highlights the need to learn more about individuals' understanding of this issue. To help achieve this objective we developed a new metric for the assessment of subjective risk judgments for combined hazards which, based on the results of the two studies reported here, has demonstrated good validity. Furthermore, our second study is, to the best of our knowledge, the first to assess domain-expert's risk judgments for a combined hazard that presents a synergistic risk. Our studies have enabled us to identify a number of possible explanations for why some individuals make veridical judgments of synergistic risks. These include the ease with which a mental model of the underlying mechanism can be formulated, and the extent to which the judge possesses both domain-specific knowledge and judgmental experience concerning the target combination. Consequently, we recommend that future research explores the efficacy of risk communications that aim to develop these characteristics in individuals. However, a vital tool for assessing the relative effectiveness of such risk communication messages is a valid method of measuring the audiences' risk judgments for combined hazards. We believe that our results demonstrate that the composed format introduced here is capable of fulfilling this important task.

Chapter Four: Helping Individuals to Understand Synergistic Health Risks: An Assessment of Antecedent and Probabilistic Message Contents

Abstract

Accumulating evidence shows that certain hazard combinations interact to present synergistic health risks. However, little is known about the most effective ways of helping individuals to understand this risk concept. More specifically, there is an absence of empirical research that has assessed the relative efficacy of messages that explain either the antecedent mechanism and/or the probabilistic components of synergistic health risks. In an experiment designed to address this issue, we presented UK-based participants with messages concerning the synergistic risk of developing oesophageal cancer for individuals who consume both tobacco and alcohol. Relative to a control group, we compared the effectiveness of messages featuring content detailing the antecedent, the probabilistic risk, or both. Our results showed that messages containing details of both the antecedent and probabilistic risk were most effective at enabling individuals to understand that the alcohol-tobacco combination presents a synergistic risk. In addition, large improvements in the accuracy of incidence frequency estimates were observed amongst individuals who received probabilistic information, and the highest relative increase in willingness to adopt precautionary behaviours was observed amongst individuals who received the antecedent information only. Importantly, these findings indicate that parties interested in communicating synergistic risks should consider how different message content may elicit different levels of comprehension and behavioural intentions. Furthermore, in contrast to previous findings, our study demonstrates that

risk messages can be both effective *and* efficient in helping individuals to acquire a significantly greater understanding of synergistic risks. Acquiring such knowledge could lead to significant improvements in health-related decisions concerning combined hazards.

4.1. Introduction

4.1.1. Overview

Scientific evidence shows that the health risk attributable to certain hazard combinations exceeds the sum of the risk attributable to each constituent hazard (i.e., the combination presents a 'synergistic risk'). For example, epidemiological studies have found that the combined use of alcohol and tobacco results in a synergistic risk of laryngeal and oesophageal cancer (Lee et al., 2005; Talamini et al., 2002) and interactions between particular drugs, such as aspirin and warfarin, result in a synergistic risk of serious internal bleeding (Delaney, Opatrny, Brophy, & Suissa, 2007). Another example is a synergistic increase in the incidence of psychosis amongst individuals living in urban areas who also have a family history of mental illness (Van Os, Pedersen, & Mortensen, 2004). Evidence of synergistic health risks continues to accumulate (e.g., Ben et al., 2011; Takahashi & Kimura, 2010).

Several studies investigating subjective risk judgments for combined hazards have indicated that individuals often judge synergistic risks as either additive (i.e., equal to the sum of the risk attributable to each constituent hazard) or sub-additive (i.e., less than the sum of the risk attributable to each constituent hazard) risks (for a detailed taxonomy see French, Sutton, Kinmonth, & Marteau, 2006). These findings raise the concern that such underestimations of risk may impede an individual's motivation to adopt protective behaviors or to demand, political and economic actions to address synergistic risks (French et al., 2006; Leiserowitz, 2006). A further concern is that the failure to understand particular synergistic health risks by policy-makers, regulators, and medical professionals may inhibit the implementation of relevant precautionary interventions (Berenbaum, 1989; Cogliano, 1997). These concerns highlight the value of identifying effective and efficient methods of helping individuals to understand specific synergistic risks. However, empirical research regarding the communication of synergistic risks is scarce and the communication approaches that have been assessed have either been found to be unsuccessful (French et al., 2006; Hampson et al., 1998) or dependent on complex and time-consuming procedures (Bonnin-Scaon, Lafon, Chasseigne, Mullet, & Sorum, 2002). Consequently, these approaches could not be employed to efficiently bring specific synergistic health risks to the attention of large groups such as regulators, policy-makers, health practitioners, and the wider public.

Hence, there are unanswered questions concerning the most effective methods for conveying information about synergistic risks in a manner that is both efficient and easily understood by the recipients (Lipkus, 2007). Our study helps to fill some of these gaps in our knowledge. Specifically, we developed two risk messages concerning the synergistic risk of developing oesophageal cancer for individuals who consume both alcohol and tobacco. One message featured content concerning the antecedent mechanism by which alcohol and tobacco interact, and the other message featured probabilistic information concerning the likelihood of developing oesophageal cancer for individuals who use alcohol and tobacco. Our principal aim was to identify which message content best helped individuals to understand that the combination presented a synergistic risk. Our motivation for undertaking this study was to identify how to help individuals improve their understanding of synergistic health risks so that they can make informed decisions and adopt appropriate behavioral responses.

4.1.2. The Communication of Synergistic Health Risks

The term ‘synergistic risk’ refers to a cause-and-effect concept. That is, the interaction of certain hazards initiates a mechanism (i.e., a cause), which results in a risk magnitude (i.e., an effect) that is greater than the sum of the risk magnitude attributable to each hazard when operating separately. Despite featuring these two components, empirical studies concerning the communication of synergistic risks have primarily focused on assessing messages that convey only the ‘effect’ component. Specifically, the messages have depicted probabilistic risk information for both the hazard combination and each of the constituent hazards. The intention of these messages has been to encourage recipients to identify that the risk presented by the combination is greater than the sum of the risk presented by the constituents. For example, Hampson et al. (1998) employed this approach when using pie-charts and explanatory text to communicate the lung cancer risk for individuals who are exposed to tobacco smoke, radon, or both. Although slices of the pie-charts provided a proportional representation of the risk magnitude attributable to each constituent hazard and the combination, the findings indicated this approach failed to help individuals understand that the radon-tobacco combination presents a synergistic risk (see Lipkus & Hollands, 1999). Similarly, French et al. (2006) used bar-graphs and explanatory text to convey probabilistic information concerning the additive health risk attributable to one hazard combination and the synergistic health risk attributable to a different combination. The results suggested that the bar-graphs failed to help participants differentiate between the risks attributable to each combination. By contrast, Bonnin-Scaon et al. (2002) showed that messages featuring probabilistic information can enable recipients to make relatively accurate judgments of synergistic risks. Bonnin-Scaon et al. used one-to-one training sessions to teach individuals the likelihood of developing oesophageal cancer for various levels of alcohol and tobacco consumption. In the sessions, participants received iterative feedback concerning the accuracy of their initial and revised risk estimates. Bonnin-Scaon et al. posited that it was primarily this provision of feedback that increased the participants' risk estimate calibration. Despite the reported success of this approach, it should be noted that each participant's training lasted at least one hour.

The efficacy of helping individuals to understand synergistic health risks using messages describing the antecedent mechanism remains, to the best of our knowledge, empirically untested. However, there are reasons to believe that such messages could prove effective. For instance, research concerning individual health hazards has indicated that antecedent-related information can help individuals formulate a mental model of what may cause one to develop a particular health problem and, consequently, to personalize the threat (Rothman & Kiviniemi, 1999; Sherman, Cialdini, Schwartzman, & Reynolds, 1985). In addition, research has shown that many individuals view probabilistic health risk information as insufficient, preferring to focus on understanding the potential causes of health problems and the relevant preventative actions (Boeije & Janssens, 2004; French & Hevey, 2008). Hence, in relation to synergistic health risks, risk communications that impart knowledge of the antecedent could increase the plausibility and vividness of the mechanism by which particular hazards interact. This could heighten the personal relevance of the risk, whilst also implicitly conveying how the avoidance/removal of one factor can prohibit the underlying mechanism. Moreover, a study by Dawson, Johnson and Luke (2011) found that individuals who demonstrated an awareness of synergistic health risks often expressed a belief that the increased risk was attributable to an underlying mechanism (e.g., chemical reaction between two drugs). Hence, risk messages detailing antecedent mechanisms may provide a promising approach for communicating synergistic health risks.

To our knowledge, the efficacy of communicating both the antecedent and probabilistic components of a synergistic health risk remains untested. Such communications would explicate the cause-effect process and, therefore, could help individuals appreciate how a particular synergistic risk arises and to understand the magnitude of the threat. This more 'complete' understanding of synergistic risk may help improve decisions regarding precautionary behaviors, as there would be less scope for individuals to misunderstand what initiates the antecedent and how likely it is that the adverse health outcome will occur.

4.1.3. The Present Research

In light of the limitations in the extant literature, we conducted a study with the principal aim of assessing the relative effectiveness of communicating a synergistic health risk using a message containing either antecedent or probabilistic information, or both. We assessed each message relative to a control group and measured the extent to which each of these messages improved participants' risk model (i.e., sub-additive, additive, or synergistic risk) judgments and the accuracy of their risk magnitude estimates for the hazard combination. Furthermore, we made relative assessments of each message's affective impact and capacity to influence professed behavioral intentions, and we assessed the extent to which each message was understood and trusted.

4.1.3.1. Alcohol, Tobacco and Oesophageal Cancer

In our study, all participants were presented with information regarding the synergistic risk of developing oesophageal cancer for individuals who use both alcohol and tobacco. We selected the alcohol-tobacco combination for several reasons. First, this synergistic risk is well-evidenced in several epidemiological studies (e.g., Castellsague et al., 1999; Lee et al., 2005; Zambon et al., 2000). Second, several authors have expressed support for a hypothesized biological mechanism underling the synergy (Blot, 1992; Boffetta & Hashibe, 2006; Flanders & Rothman, 1982), and this hypothesis has been upheld by evidence from several bio-physics studies (Du et al., 2000; Howie et al., 2001; Squier, Cox & Hall, 1986). Specifically, consumed alcohol acts as a solvent that lines the mucosa of the aero-digestive organs, and this increases the extent to which carcinogenic toxins in tobacco stick to and penetrate the tissue of these organs. Hence, the mechanism underlying this synergistic risk is reasonably well understood and could be explained to lay individuals. Third, smoking and alcohol consumption are prevalent activities in many countries (World Health Organization, 2002), and research suggests that many individuals engage in both behaviors (Bien & Burge, 1990; Dierker et al., 2006). Finally, smoking and alcohol consumption are two of the leading risk factors for oesophageal cancer and less than one in ten people survive for ten years following diagnosis (Cancer Research UK, 2011). Thus, the risk of oesophageal cancer for individuals who both smoke and drink remains a critical public health issue. Consequently, this is an important synergistic health risk and there is information (regarding both the antecedent and risk magnitude) available for dissemination which could potentially influence decisions and behaviors.

4.1.3.2. Communication Format and Contents

The probabilistic data we presented to participants was conveyed via three 'icon arrays' (a.k.a., population figures or pictograms). Each array comprised a 10 x 10 grid of square-shaped icons with a white/black square representing an individual unaffected/affected by esophageal cancer. We employed icon arrays as this form of graphical analogy is effective in (a) illustrating the proportional relationship between the numerator (i.e., those affected by the disease) and the denominator (i.e., the population), (b) increasing the accuracy of risk magnitude judgments, (c) facilitating efficient processing of probabilistic data, and (d) communicating risk magnitudes to individuals with varying numerical proficiency (Galesic, Garcia-Retamero & Gigerenzer, 2009; Garcia-Retamero & Galesic, 2010; Timmermans, Ockhuysen-Vermey & Henneman, 2008). We used separate icon arrays to convey the frequency with which the following develop oesophageal cancer: (i) smokers (ii) drinkers, and (iii) those who are both smokers *and* drinkers. All three arrays were presented to participants simultaneously with the intention of enabling them to identify that the risk presented by the alcohol-tobacco combination is greater than the sum of the risk presented by either substance alone. Each array was supported by explanatory text.

The information presented to participants concerning the antecedent mechanism underlying the alcohol-tobacco synergy was based on the studies discussed above. Details of the mechanism were conveyed using three simplified pictorial diagrams, accompanied by explanatory text, depicting the oesophagus during exposure to alcohol and tobacco (see Method for details). This format provided some parity with the format employed in the 'probabilistic condition' (i.e., three graphical images with supporting text), and research has shown that pictures are effective in helping individuals to develop mental models and a deep comprehension of concrete processes (Butcher, 2006; Glenberg & Langston, 1992).

4.1.3.3. Risk Comprehension and Numeracy

The ability to understand and process probabilistic and mathematical concepts (a.k.a., numeracy) has been shown to vary significantly between individuals (Lipkus et al., 2001; Peters, 2008) and inadequate numerical skills can inhibit the comprehension of numeric health risk information (Peters, 2008; Reyna & Brainerd, 2007). Hence, we also assessed whether participants' numerical skills affected their ability to identify, from the messages presented, the risk model and risk magnitude attributable to the alcohol-tobacco combination. If numeracy skills were found to moderate comprehension of this synergistic risk it could be indicative of a weakness in our messages' capacity to facilitate comprehension amongst individuals of differing levels of numeracy.

4.2. Method

4.2.1. Participants

One-hundred-and-twenty-seven postgraduate management students (57 men, 70 women) aged 20 to 36 (M = 24.63, SD = 3.11) participated in this study during a lecture at a UK university in February 2011.

4.2.2. Materials

Participants reviewed one of four A4-sized booklets, each of which contained the following opening statement: "*Research evidence shows that regularly drinking alcohol can increase the chance of developing cancer of the esophagus (the food-pipe that links* *the mouth to the stomach).*[12] *Research evidence also shows that regularly smoking tobacco can increase the chance of developing cancer of the esophagus*." All booklets contained a message stating that within the booklet the terms 'heavy smoker' and 'heavy drinker' referred, respectively, to a person who (a) smokes more than 25 cigarettes per day, and (b) consumes the equivalent of two standard size bottles of wine per day.

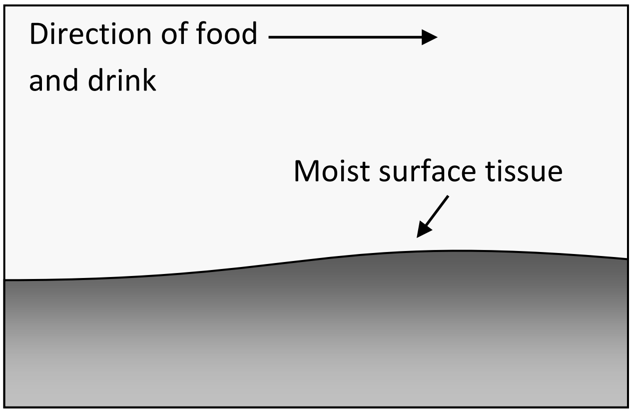
One version of the booklet (control condition) contained no further information than that described above. Hence, participants in this condition were only made aware that using alcohol or tobacco increases the risk of oesophageal cancer. They did not receive any information concerning the increased (i.e., synergistic) risk from using both substances.

The second version of the booklet (antecedent condition) provided participants with additional information, in the form of text and pictorial diagrams, describing the hypothesized mechanism that underlies the increased risk of developing oesophageal cancer for people who both smoke and drink. The text read: "*Research evidence shows that when a person drinks alcohol and smokes tobacco, the alcohol acts like a glue that causes the toxins in the smoke to stick to the moist tissue lining of the esophagus. The toxins are then more able to penetrate the tissue in the esophagus. This increases the chance of developing cancer in this area of the body*. *The three diagrams on the following page illustrate the process described above*". Participants then reviewed three diagrams illustrating the mechanism (see Figure 5). Each diagram was 82cm x 53cm, printed in grey-scale, and accompanied by one sentence describing the process depicted in the diagram. Hence, participants in this condition were informed that the risk of developing

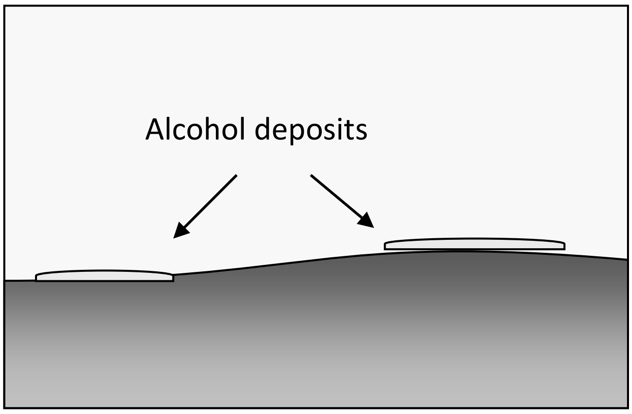
[12] The materials employed in the study featured the US English (cf. UK English) spelling of the words 'oesophagus' and 'oesophageal'. This was to facilitate easier comprehension and recognition of this unusual and, possibly, unfamiliar term amongst the participants.

oesophageal cancer increases for individuals who both smoke and drink, but not informed of the magnitude of the increase.

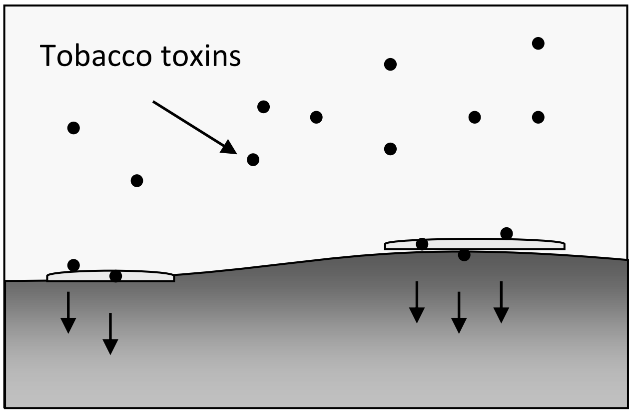
Figure 5. Three simplified diagrams illustrating the hypothesized antecedent mechanism underlying the synergistic risk of oesophageal cancer attributable to the combined use of alcohol and tobacco.



1. A cross-sectional view of the tissue lining of the esophagus.



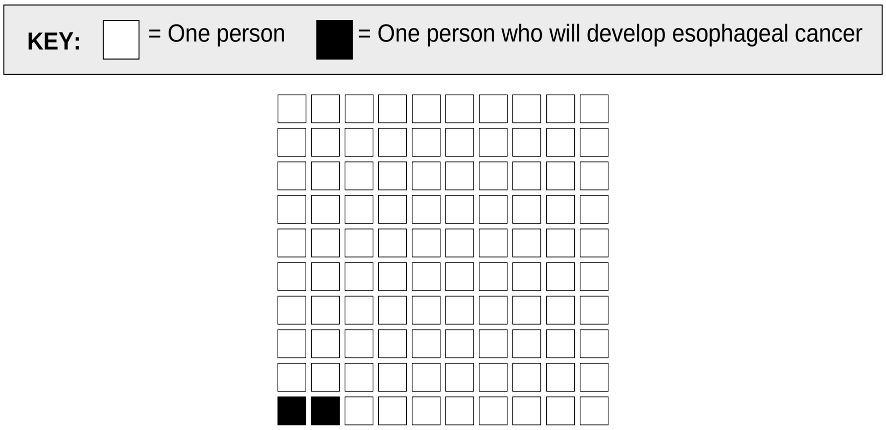
2. Small deposits of alcohol stick to the tissue lining of the esophagus.



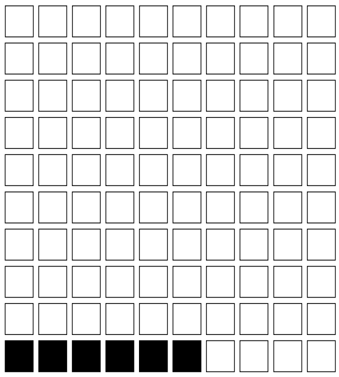
3. Tobacco toxins stick to the alcohol deposits and penetrate the tissue lining.

The third booklet (probabilistic condition) provided participants with information in the form of text and pictorial diagrams. In this version, the text read: "*On the following page you will see three diagrams. Each of the three diagrams represents a population of 100 people. Each square represents one person. A black square represents a person who will develop esophageal cancer during their lifetime. The data in these diagrams is based on the results of scientific research*." Participants then reviewed three icon arrays which each contained 100 squares (see Figure 6). In the first two icon arrays, two and six squares, respectively, were shown in black (to the left of the bottom row) and the arrays were accompanied by the sentences: "*A population of 100 heavy smokers*" and "*a population of 100 heavy drinkers*", respectively. The third array showed twenty-nine squares in black across the bottom three rows, with all other squares in white. Beneath this array was the sentence: "*A population of 100 people, each one of whom is both a heavy smoker* ***and*** *a heavy drinker*." Each array was 47m x 47cm, and printed in black-and-white. The three arrays were accompanied by a 'key' indicating that a white/black square represented one person who would not/would develop oesophageal cancer. Hence, participants in this condition were only provided with probabilistic information (in pictorial form) from which they could infer that the alcohol-tobacco combination presented a greater risk of developing oesophageal cancer than the sum of the risk for either substance alone.

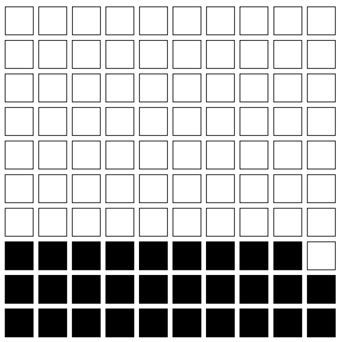
Figure 6. Three icon arrays illustrating, respectively, the number of individuals who will develop oesophageal cancer amongst a population of 100 heavy smokers, 100 heavy drinkers, and 100 individuals who both smoke and drink.



A population of 100 heavy smokers.



A population of 100 heavy drinkers.



A population of 100 people; each one of whom is both a heavy smoker **and** a heavy drinker.

The additional information provided in the fourth booklet included identical versions of that featured in both the antecedent condition and in the probabilistic condition. The antecedent-related information/diagrams were presented first, followed by the sentence "*The extent to which the harmful interaction between alcohol and tobacco increases the chance of developing esophagus cancer is represented in the three diagrams below*". The probability-related information/diagrams were then presented. Thus, participants in this condition, consistent with the chronology of the cause-effect process, first reviewed information that explained the antecedent and then the probabilistic/synergistic risk.

The participants in all four conditions read the assigned information booklet and, at their own pace, then moved on to immediately complete the same questionnaire. They were instructed not to look in the informational booklet whilst completing the questionnaire (compliance with this instruction was monitor by the experimenters and no breaches were observed). The questionnaire commenced with the following paragraph: "*Research evidence shows that a person who is a heavy smoker has a 2 in 100 chance of developing esophageal cancer during their lifetime. Research evidence also shows that a person who is a heavy drinker has a 6 in 100 chance of developing esophageal cancer during their lifetime*." Hence, all participants were made aware of the likelihood of developing oesophageal cancer for individuals who are either heavy smokers or heavy drinkers only. Following this paragraph, participants were asked to consider the likelihood of an individual developing oesophageal cancer if that individual was both a heavy smoker and a heavy drinker. They were asked to state, using a multiple-choice response format, whether they judged this likelihood to be "*less than*", "*equal to*", or "*more than*" the likelihood for an individual who is a heavy smoker only, "*added to*" the likelihood for an individual who is a heavy drinker only. The layout, style, and content of this judgment task were developed in accordance with guidelines outlined by Osterlind (1997) for the construction of multiple-choice response items. Participants were then presented with a second judgment task which asked: "*Out of a population of 100 people, each of whom is a heavy smoker **and** a heavy drinker, how many of them do you estimate will develop esophageal cancer during their lifetime*?" (see Appendix Four).

In the subsequent part of the questionnaire, participants used Visual Analogue Scales (VAS), numbered 1 to 7, to state how worried ('not at all worried' = 1, 'extremely worried' = 7) and frightened ('not at all frightened' = 1, 'extremely frightened' = 7) he/she would be about developing oesophageal cancer during their lifetime if he/she were both a heavy smoker and a heavy drinker. Participants also used seven-point VASs to state how likely ('not at all likely' = 1, 'extremely likely' = 7) it is that, based on the information he/she read in the booklet, he/she would (a) quit smoking, (b) quit drinking, (c) reduce smoking, and (d) reduce drinking. Participants were asked to make all responses to these questions 'as if he/she was' a heavy smoker and drinker, because it was anticipated that a majority of participants would probably not be both heavy smokers *and* drinkers (consistent with this prediction, 94% of our participants reported either smoking only [at least once-a-day], drinking only [at least once-a-week], or doing neither).

Finally, participants used seven-point VASs to describe the extent to which they understood ('not at all easy to understand' = 1, 'extremely easy to understand' = 7) and trusted ('not at all trustworthy' = 1, 'extremely trustworthy' = 7) the information in the booklet.

4.2.2.1. Measurement of Numeracy

Participants completed eight numerical questions established by Lipkus, Samsa and Rimer (2001). For familiarization, participants initially read an example question (with the correct answer provided) prior to completing the questions. An example of one of the eight questions is "*Which of the following numbers represents the biggest chance of getting a disease? 1 in 100, 1 in 1000, 1 in 10?*" The fifth question comprised two sub-questions ('a' and 'b') which we treated as two separate items (see Appendix Five). Hence, participants could achieve a maximum score of nine.

4.2.3. Design

The study followed a 4 (risk communication: control, antecedent, probabilistic, antecedent+probabilistic) x 2 (numeracy: more, less) between-subjects design. The two principal dependent variables were (a) risk model judgments (sub-additive, additive, or synergistic) and (b) frequency estimates (e.g., 29 out of 100).

4.2.4. Procedure

Approximately 40 copies of each of the four booklets were manually shuffled into one pile and then distributed amongst the participants. Participants were informed that they had unlimited time to review the booklet and to complete the questionnaire. Participants were advised not to consult any other resources or persons during the experiment. The procedure was supervised by three experimenters.

4.2.5. Analysis

Hierarchical loglinear analysis was employed to test for main effects and interactions between categorical variables, and significant results were further analyzed using chi-square (χ^2) tests. Analyses of variance (ANOVAs) were employed to assess the influence of risk messages on continuous dependent variables (e.g., VAS responses), and significant differences were analyzed using Bonferroni post hoc tests.

4.3. Results

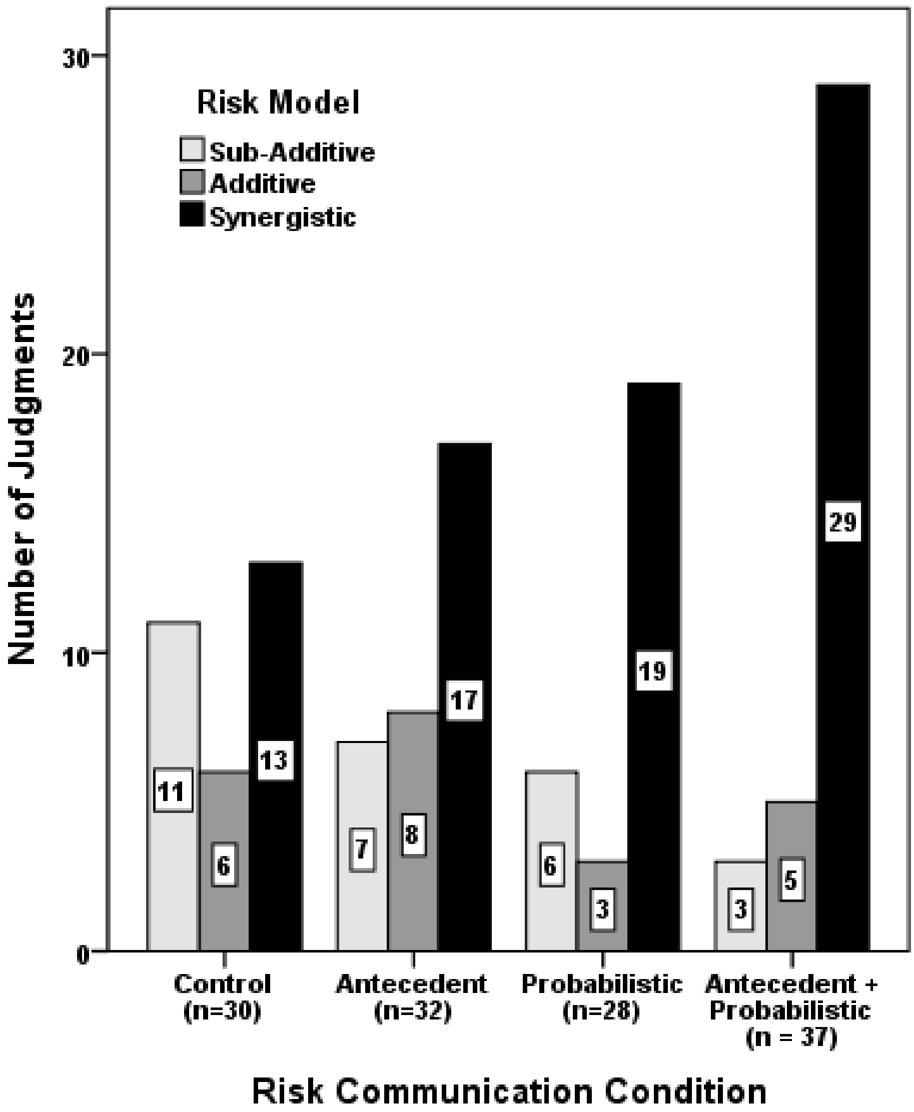
4.3.1. Numeracy of Participants

The mean numeracy score was 7.15 (*SD* = 1.73; *Md* = 7), and scores ranged from 1 to 9. Participants were split into two groups (more or less numerate) according to the group median score. Hence, 48.8% (*n* = 62) of participants with 8 or 9 items correct were classified as more numerate, and 51.2% (*n* = 65) of participants with 7 or fewer correct items were classified as less numerate (see Galesic et al., 2009; Garcia-Retamero & Galesic, 2010; Keller & Siegrist, 2009 for similar procedures). As observed here, on extant numeracy scales it is commonplace to obtain a skewed distribution of scores where the median score is higher than the mid-point on the scale (Peters, 2011).

4.3.2. Data Preparation

Categorical risk model judgments for each of the four risk communication groupings are displayed in Figure 7. To determine whether three-way loglinear analyses (e.g., risk model x risk communication x numeracy) could be performed, we assessed whether the data met the test assumption that no less than 20% of the cells should have expected frequencies less than 5 (Field, 2009). As 67% of cells featured expected frequencies less than 5, the data did not meet this assumption. To address this issue, the 'sub-additive' and 'additive' categories were collapsed into one category, resulting in two categories for the risk model variable (i.e., 'synergistic' and 'non-synergistic'). The data then met the test assumptions, and the three-way analysis was viable. Collapsing categories into dichotomous groups is appropriate for a hierarchical loglinear analysis where the research aims (i.e., assessing whether or not participants judged that the hazard combination presented a synergistic risk) are not affected (Field, 2009).

Figure 7. Participants' risk model judgments concerning the risk of developing oesophageal cancer for individuals who are both heavy smokers and heavy drinkers. Judgments shown for each of the four risk communication conditions.



4.3.3. Risk Model Judgments, Risk Communication and Numeracy

To assess whether participants' risk model judgments varied according to risk communication and/or numeracy, we performed a three-way loglinear analysis: risk model x risk communication x numeracy. This identified a significant main effect for risk model, χ^2 (1) = 6.68, p = 0.01. The main effect for risk model was attributable to the greater proportion of participants, across the whole sample, who judged that the combination would present a synergistic risk (61%) rather than a non-synergistic risk (39%), χ^2 (1) = 6.62, p < 0.01. Furthermore, the main effect for risk model was qualified by a two-way interaction between risk model and risk communication, χ^2 (3) = 9.90, p < 0.05. No other significant interactions or main effects were found, χ^2s (3) < 2.68, ps > 0.05. Hence, participants' risk judgments did not differ significantly according to numerical ability and this was the case irrespective of the risk communication participants reviewed.

To investigate the identified two-way interaction between risk model and risk communication, chi-square analyses of participants' risk model judgments were performed for each risk communication grouping. To address the increased risk of a Type I error when performing these multiple comparisons, a Bonferroni correction (p = 0.05/4 = 0.0125) was employed. In the control condition, there was no significant difference, χ^2 (1) = 0.53, p > 0.05, between the proportion of participants who judged that the hazard combination would present a synergistic risk (43%) and a non-synergistic risk (57%). Similarly, there was no significant difference between these two proportions in (a) the antecedent condition (53% synergistic risk, 47% non-synergistic risk), χ^2 (1) = 0.13, p > 0.05, or (b) the probabilistic condition (68% synergistic risk, 32% non-synergistic risk), χ^2 (1) = 3.57, p > 0.05. However, in the antecedent+probabilistic condition, a significantly greater proportion of participants (78%) judged that the combination would present a synergistic risk (cf. non-synergistic risk), χ^2 (1) = 11.91, p < 0.001.

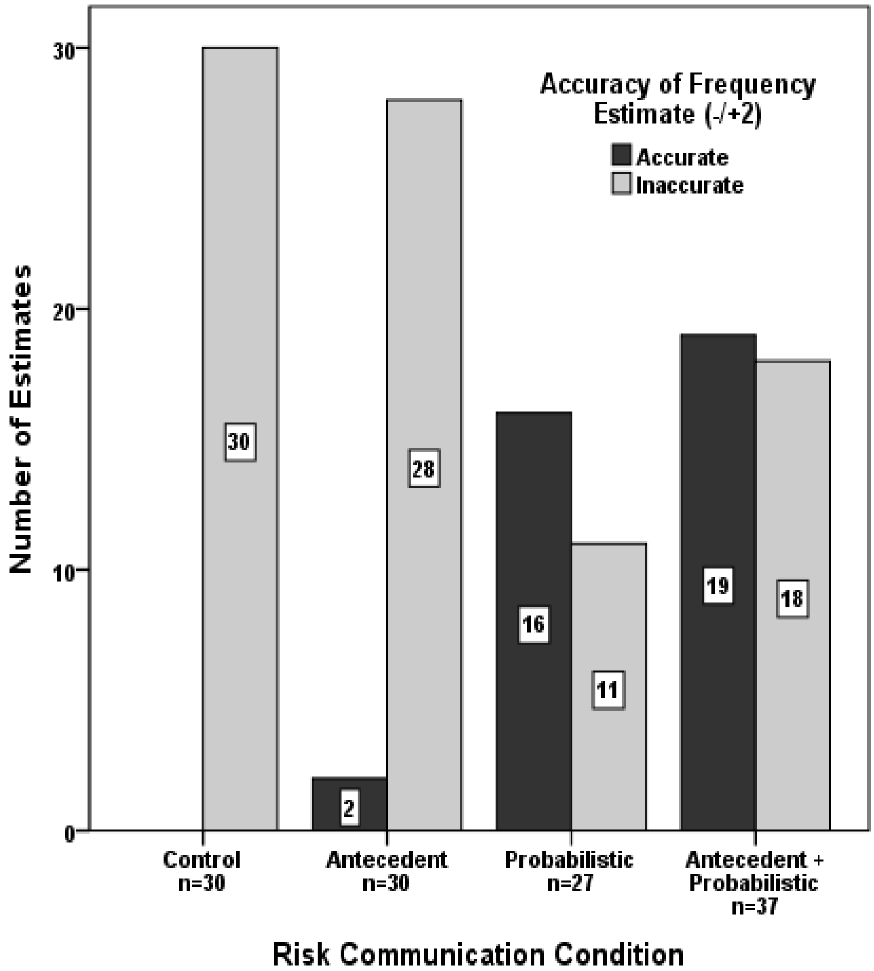
Chi-square tests were employed to assess whether the risk model judgments made by participants in the (i) antecedent (ii) probabilistic or (iii) antecedent+probabilistic conditions differed significantly from those in the control condition. A Bonferroni correction was employed (p = 0.05/3 = 0.017). The results revealed that the participants' risk model judgments in the antecedent condition and the probabilistic condition did not differ significantly from participants' judgments in the control condition, χ^2s (1) <= 3.52, *p*s > 0.05. By contrast, a significantly greater proportion of participants in the antecedent+probabilistic (cf. control) condition judged that the hazard combination would present a synergistic risk, χ^2 (1) = 8.70, $p < 0.01$.

4.3.4. Accuracy of Frequency Estimates, Risk Communication and Numeracy

As described above, participants were asked to estimate how many individuals, each of whom is a heavy smoker *and* a heavy drinker, would develop oesophageal cancer during their lifetime. Calculations based on data reported by Cancer Research UK (2009) and Zambon et al. (2000) indicate that 29 of 100 such individuals will develop oesophageal cancer in their lifetime. The accuracy of participants' frequency estimates was assessed in relation to this statistic. The distribution of participants' estimates, which ranged from 1 to 90, demonstrated a peak from 27 to 31, followed by a drop in responses beyond these limits. This indicated participants either did not know the correct frequency, or knew the correct frequency within ±2%. Thus, the frequency estimate variable was transformed into a dichotomous categorical variable (accuracy: accurate, inaccurate), with estimates from 27 to 31 categorized as accurate, and all other estimates deemed inaccurate. For a similar approach to assessing the accuracy of risk/frequency judgments see Galesic et al. (2009).

Categorical frequency estimates for each of the four risk communication groupings are displayed in Figure 8. A three-way loglinear analysis (accuracy x risk communication x numeracy) was performed to assess whether participants' estimates varied according to risk communication and/or numeracy. This identified a significant main effect for accuracy, χ^2 (1) = 20.75, p < 0.001. The main effect for accuracy was attributable to the greater proportion of participants, across the whole sample, who provided inaccurate (70%) rather than accurate (30%) frequency estimates, χ^2 (1) = 20.16, p < 0.001. Furthermore, the main effect for accuracy was qualified by a two-way interaction between accuracy and risk communication, χ^2 (3) = 49.42, p < 0.001. However, no other significant interactions or main effects were found, χ^2s (3) <= 3.99, ps > 0.05. Hence, the accuracy of participants' frequency estimates did not differ significantly according to numerical ability and this was the case irrespective of the type of risk message reviewed.

Figure 8. Participants' frequency estimates concerning the likelihood of developing oesophageal cancer for individuals who are both heavy smokers and heavy drinkers. Estimates displayed in dichotomous categories of accurate (+/- 2 of the 29/100 likelihood reported by Zambon et al., 2000) vs. inaccurate, and shown for each of the four risk communication conditions.



To investigate the identified two-way interaction between accuracy and risk communication, chi-square analyses of participants' frequency estimates were performed for each risk communication grouping. A Bonferroni correction (p = 0.05/4 = 0.0125) was employed. For the control condition, the test could not be computed as 100% of participants provided inaccurate frequency estimates. Similarly, 93% of participants in the antecedent condition provided inaccurate estimates and, consequently a significant difference, χ^2 (1) = 22.53, p < 0.001, was observed between the proportion of accurate and inaccurate estimates. Separate tests for the probabilistic and antecedent+probabilistic conditions both revealed no significant difference, χ^2s (1) < 0.94, *p*s > 0.05, between the proportion of accurate and inaccurate estimates in each condition (probabilistic/antecedent+probabilistic condition: 59/51% accurate, 41/49% inaccurate).

Tests were performed to examine whether the accuracy of participants' frequency estimates in the antecedent, probabilistic, and antecedent+probabilistic conditions differed from participants' estimates in the control condition. A Bonferroni correction was employed ($p = 0.05/3 = 0.017$). The results revealed that the accuracy of participants in the control and antecedent conditions did not differ significantly, χ^2 (1) = 2.07, $p > 0.05$. By contrast, a significant difference was identified between the accuracy of participants estimates in the control and (i) the probabilistic condition, χ^2 (1) = 24.72, $p < 0.001$, and (ii) the antecedent+probabilistic condition, χ^2 (1) = 21.50, $p < 0.001$. That is, participants in both the probabilistic and the antecedent+probabilistic conditions provided a significantly greater proportion of accurate estimates than participants in the control condition.

4.3.5. Affective Responses, Behavioral Intentions, Comprehension and Trust

For each of the four risk communication conditions, participants' mean responses on the seven-point VASs are displayed in Table 8. Independent measures ANOVAs were performed to assess whether participants' responses varied according to the conditions. This identified that there was no significant difference between the four conditions in terms of (i) the extent to which the information in each booklet was trusted ($M = 4.67$, $SD = 1.50$) and understood ($M = 5.76$, $SD = 1.26$), $Fs(3, 123) < 1.38$, *p*s > 0.05, (ii) affective evaluations, such as worry ($M = 5.15$, $SD = 1.54$) and fright ($M = 4.74$, $SD = 1.68$), $Fs(3, 123) < 2.02$, *p*s > 0.05, and (iii) the likelihood of quitting drinking ($M = 3.89$, $SD = 1.79$), reducing drinking (*M* = 4.85, *SD* = 1.82), or reducing smoking (*M* = 5.07, *SD* = 1.77), *F*s(3, 123) < 1.59 *p*s > 0.05. However, the likelihood of quitting smoking did differ significantly between the risk communication conditions, $F(3, 123) = 3.27$, $p < 0.05$. A Bonferroni post hoc test ($p = 0.05/4 = 0.0125$) revealed that participants in the antecedent condition (*M* = 4.53, *SD* = 1.87) were significantly ($p = 0.04$) more likely to report they would quit smoking (cf. participants in the control condition) if they were both a heavy smoker and a heavy drinker (*M* = 3.30, *SD* = 1.56); no other significant (*p*s > 0.05) pairwise comparisons were identified.

Table 8. Mean ratings (standard deviations) in response to questions concerning the risk of developing oesophageal cancer for individuals who are both regular smokers and regular drinkers.

Question (abbreviated form)	***Risk Communication Materials Reviewed*** Control *(n = 30)*	Antecedent *(n = 32)*	Probabilistic *(n = 28)*	Antecedent+ Probabilistic *(n = 37)*	Overall Mean *(N = 127)*
Worried if regular smoker and drinker? *(1 = Not at all worried, 7 = Extremely worried)*	4.63 (1.40)	5.56 (1.65)	5.29 (1.58)	5.11 (1.47)	5.15 (4.74)
Frightened if regular smoker and drinker? *(1 = Not at all frightened, 7 = Extremely frightened)*	4.23 (1.38)	5.06 (1.70)	4.82 (1.79)	4.81 (1.76)	4.74 (1.68)
Quit smoking if regular smoker and drinker? *(1 = Not at all likely, 7 = Extremely likely)*	3.30 (1.56)	4.53 (1.87)	4.54 (1.92)	4.05 (1.72)	4.10 (1.81)
Quit drinking if regular smoker and drinker? *(1 = Not at all likely, 7 = Extremely likely)*	3.40 (1.48)	4.13 (1.98)	4.11 (1.69)	3.92 (1.90)	3.89 (1.79)
Reduce smoking if regular smoker and drinker? *(1 = Not at all likely, 7 = Extremely likely)*	4.63 (2.06)	5.47 (1.67)	5.36 (1.55)	4.86 (1.74)	5.07 (1.77)
Reduce drinking if regular smoker and drinker? *(1 = Not at all likely, 7 = Extremely likely)*	4.57 (1.89)	4.88 (1.90)	5.25 (1.67)	4.76 (1.83)	4.85 (1.82)
Understood Risk Communication Materials? *(1 = Not at all easy to Understand, 7= Extremely easy to understand)*	5.63 (1.35)	5.66 (1.07)	6.18 (1.02)	5.62 (1.46)	5.76 (1.26)
Trusted Risk Communication Materials? *(1 = Not at all trustworthy, 7 = Extremely trustworthy)*	4.37 (1.73)	4.63 (1.48)	4.96 (1.53)	4.73 (1.31)	4.67 (1.50)

4.4. Discussion

Our results show that messages which convey evidence-based details of the antecedent mechanism, the resultant probabilistic risk, or both of these, each has its own strengths in helping individuals to understand a synergistic health risk; suggesting that message content should be selected according to the communicator's objectives. Specifically, we found that the message concerning both the antecedent mechanism *and* the resultant risk magnitude was the only approach that led to a significant improvement in the veridicality (i.e., consistent with empirical data) of individuals' risk model judgments. This suggests that, where a communicator's principal aim is to help individuals understand that a hazard combination presents a synergistic risk, details of both components should be conveyed. We also found that the provision of probabilistic information, either alone or in conjunction with antecedent information, can lead to significant improvements in the extent to which individuals accurately understand the risk magnitude attributable to a particular hazard combination. This indicates that messages detailing the probabilistic risk alone are most likely to be appropriate when the communicator's sole objective is to help impart knowledge of synergistic risk magnitudes. Furthermore, our study suggests that a message detailing only the antecedent mechanism of a synergistic health risk may be most effective in influencing health-protective behavioral intentions. That is, a message which focuses the recipient's attention on the cause of a synergistic risk may help that person recognize that the threat posed by the hazard combination can be reduced/eliminated by the removal of one of the hazards. Furthermore, the absence of variation in affective reactions (i.e., worry and fright) between the four conditions indicates that evidence-based messages concerning synergistic health risk may be particularly appropriate when the communicator's motive is to facilitate informed decision-making rather than to arouse fear or provoke disproportionate precautionary behaviors.

Beyond these key findings, there are additional aspects of our results that require further consideration and which provide useful insights into the communication of synergistic health risks. First, the frequency estimates of participants in the two probabilistic conditions (cf. control condition) show that the icon arrays helped just over half of them to acquire precise knowledge of the risk magnitude. On one hand, this finding shows that, in contrast to the results of previous studies that have not employed icon arrays (French et al., 2006; Hampson et al., 1998), probabilistic information about synergistic health risks can be effectively *and* efficiently conveyed using visual aids. This relative success is consistent with other studies that have demonstrated the capacity of icon arrays to substantially improve the accuracy of risk estimates (Galesic et al., 2009; Garcia-Retamero & Galesic, 2010). On the other hand, just less than half of the participants in our two probabilistic conditions did not make accurate risk estimates for the alcohol-tobacco combination. This highlights a potential limitation of this approach which, according to our findings, cannot be attributed to differences in numerical ability. Hence, there is further scope for identifying (a) how probabilistic information concerning synergistic risk magnitudes may be conveyed with greater effectiveness and (b) what factors may moderate the comprehension of probabilistic information concerning synergistic risks.

Second, our findings indicate that individuals best understand that a hazard combination presents a synergistic health risk when they are informed of both the underlying mechanism and the resultant risk. We suggest this is because the antecedent+probabilistic message provides individuals with a more complete mental model of the hazard combination's physical interaction and the likelihood of the health-related consequences. This explanation is consistent with studies that show risk comprehension can be enhanced by messages that develop an individual's mental model of a hazardous process (Bostrom, 2008; Bostrom, Fischhoff & Morgan, 1992). Cleary, an alternative explanation for the relative effectiveness of the antecedent+probabilistic message could be that the message presented a greater quantity of information and, that alone, was more persuasive. However, this explanation is not supported by our finding that participants in the antecedent+probabilistic condition (cf. those in the three other conditions) found the information presented to be no more/less trustworthy or comprehendible. That is, participants' risk model judgments appeared to be more influenced by extent to which the message facilitated a more complete understanding of the synergistic risk concept than by the credibility or clarity of the evidence presented.

Third, previous studies indicate that individuals are typically (a) interested to know what causes particular health problems, as this can help them to identify what preventative action they could take and (b) more likely to make behavioral decisions based on case-based, concrete information as opposed to statistical, abstract information (see Rothman & Kiviniemi, 1999). This could explain why participants in our antecedent condition (cf. control condition) reported being significantly more likely to quit smoking. However, this interpretation then presents the question of why participants in the antecedent+probabilistic condition did not also report being more likely to quit smoking? We speculate that this may have been because the probabilistic information attenuated the impact of the antecedent information. In particular, a 'recency-effect' may have been elicited in which the latter part of the message became dominantly salient in the minds of the participants, reducing the impact of the antecedent information (Hertwig, Barron, Weber, & Erev, 2004). Equally, the probabilistic information may have served to decrease the perceived threat posed by the alcohol-tobacco interaction, because the icon array may have been effective at highlighting that the proportion of heavy smokers and drinkers unaffected by esophageal cancer was larger than the affected proportion (Garcia-Retamero, Galesic, & Gigerenzer, 2009; Visschers et al., 2009). Whatever the cause, our results suggest that those wishing to communicate information about synergistic health risks should be mindful of how latter aspects of the message may impact upon the effects of previous aspects.

4.4.1. Limitations and Future Directions

Our study has some limitations that could be addressed in future research. First, our messages only conveyed details of the synergistic risk of developing oesophageal cancer for heavy smokers/drinkers. Consequently, we cannot comment on whether our results would be replicated for messages concerning other hazard combinations, different magnitudes of synergistic risk, or for other adverse health outcomes. Second, our use of a well-educated sample limits our ability to generalize our findings to populations with different educational backgrounds. Similarly, because our sample consisted mainly of individuals who were not smokers *and* drinkers, we cannot determine whether our messages would influence the behavior intentions of individuals who do smoke *and* drink, particularly when such individuals are addicted to either/both substances. Third, we presented our messages using specific visual formats because extant studies have highlighted the efficacy of these approaches. However, we acknowledge that other formats could prove more effective and that this is something future studies could assess. Fourth, we recognise that the participants' accuracy judgments may reflect the extent to which they successfully memorised, rather than understood, the probabilistic information. Finally, the risk messages we employed were designed to empirically assess the extent to which each specific message would enable the recipient to *infer* that the combination presents a synergistic risk. Therefore, it is important to recognise that the efficacy of these messages could be substantially enhanced by additional information which *explicitly* conveys the fundamental purpose of the communication.

4.5. Conclusion

Our study has addressed a need to identify message contents that are both effective *and* efficient in helping individuals to understand synergistic health risks. Importantly, our results highlight the specific merits and potential weaknesses of using messages that convey information about the antecedent and/or probabilistic components of this risk concept. Specifically, messages that explain both components may provide the most effective approach for enabling individuals to understand both the risk model and magnitude attributable to specific hazard combinations. Furthermore, in comparing our results with those obtained in previous studies, it appears that the particular visual format employed may also influence the effectiveness of messages that convey probabilistic information about synergistic risks. Our findings could be utilized in the design of communications concerning synergistic health risks and, consequently, improve important health-related decisions concerning combined hazards. However, further research is still needed to explore alternative approaches that can help individuals to understand the increasing number of synergistic health risks that are being identified by the scientific community.

Conclusion

The findings presented in this thesis make several valuable contributions towards developing a better understanding of people's judgments of synergistic risks (see Table 9 for a summary of the principlal contributions). Specifically, the findings indicate that many people believe that combined hazards present additive risks or, to some extent, weakly synergistic risks. Furthermore, in contrast to the results of several previous studies, the studies found little evidence to suggest that individuals have a tendency to employ sub-additive risk models for combined hazards. Hence, the present findings are encouraging, as they suggest that many individuals could/do make veridical risk judgments for combined hazards that present synergistic risks. However, it is of concern that other results presented here also indicate that there are instances where individual's risk judgments for combined hazards are not veridical. For example, the findings show that (a) some individuals may be unaware of the synergistic risk concept, (b) few individuals believe that combined hazards can present higher magnitudes of synergistic risk, and (c) there appears to be subjective epistemic uncertainty regarding the risk model attributable to both familiar (e.g., the control groups' judgments for the alcohol-tobacco combination in Chapter Four) and unfamiliar (e.g., the non-experts' judgments for the aspirin-clopidogrel combinations in Chapter Three) hazard combinations. This highlights the value of the additional evidence presented in this thesis which identifies the factors that may be inherent in the 'more veridical' judgments of synergistic risks. For instance, the findings presented here suggest that the individuals who make veridical judgments of synergistic risks may have risk-related knowledge of the target hazard combination, judgmental experience concerning the risk attributable to the combination and/or formulated a mental model of the mechanism underlying the synergistic risk. Importantly, Chapter Four shows how such findings can be utilised in the development of risk messages that aim to help individuals to better understand synergistic risks. Specifically, this latter study has shown that significant improvements in individual's understanding of a synergistic risk (even one of a higher magnitude) can be achieved effectively *and* efficiently by conveying details of both the antecedent mechanism and probabilistic risk.

Table 9. A summary of the three main contributions from each of the four papers presented in this thesis

Chapter	*1st Main Contribution*	*2nd Main Contribution*	*3rd Main Contribution*
One	The proportion of people who believe that synergistic risks can occur declines monotonically as the magnitude of a synergistic risk increases	Most people believe hazard combinations present additive risks or, to a slightly lesser extent, synergistic risks of low magnitude	Beliefs concerning the risk attributable to combined hazard appear to be hazard-specific rather than domain-specific
Two	Individuals who are aware of particular synergistic risks may understand that the increased risk is attributable to an antecedent mechanism	Individuals may exclude the synergistic risk model from their subjective risk judgments in favour of an additive model	There is little evidence to suggest individuals employ a sub-additive model in their subjective risk judgments for combined hazards
Three	The composed task format provides a valid method for the assessment of subjective risk judgments for combined hazards	The veridicality of lay judgments of synergistic risk may be moderated by experience, knowledge, and ease of mental model formation	Domain expertise can increase the veridicality of subjective judgments of synergistic risks
Four	Messages featuring both antecedent *and* probabilistic information most effective communicate synergistic risks	In contrast to other visual aids, icon arrays can effective impart knowledge of synergistic risk magnitudes	Messages that explain the antecedent mechanism of a synergistic risk appear most likely to influence behavioural intentions

Implications of the Research

The numbers of scientific studies that have identified synergistic risks continues to increase (e.g., Ben et al., 2011; Giapros, Drougia, Asproudis, Theocharis, & Andronikou, 2011). Interestingly, the greatest proportion of evidence of synergistic risks appears to be in the health domain. However, it is possible that this might simply be a reflection of the particular interest humans have in understanding what threatens their health and, consequently, of the support this has generated for research regarding this issue. However, as several studies have shown, there are also non-health synergistic risks and it is, therefore, logical to infer that synergistic risks could be equally prevalent across all domains (for supporting evidence see Corning, 1998). For instance, one of the primary root causes of the global financial crisis of 2007 has been cited as a combination of the high exposure to sub-prime customers by mortgage lenders combined with a continuous increase in federal interest rates (Goodhart, 2008; Shiller, 2008). It is possible that these two factors, when combined, may have presented a synergistic *default* risk that, consequently, served as a catalyst for a series of interrelated and systemic financial consequences across the world. Clearly this is a speculative point, but it illustrates that it may be vital for individuals, such as policy makers, regulators, managers, investors, etc., not to assume that, when making predictions about the likelihood of specific adverse events, sound judgments and decisions can be made based only on the risk attributable to a single hazard and/or on a simple summative risk model for multiple hazards. As the renowned economist John Maynard Keynes (Moggridge, 1972, p. 262) stated:

We are faced at every turn with the problem of Organic Unity, of Discreteness, of Discontinuity – the whole is not equal to the sum of the parts, comparisons of quantity fail us, small changes produce large effects, the assumption of a uniform and homogeneous continuum are not satisfied.

In light of the increasing identification of synergistic risks and the potential for such risks to exist in numerous contexts with far reaching implications, there is clearly much value in bringing these risks to the attention of the individuals who may be affected and/or who are responsible for their management. However, before this can be done in a manner that is both efficient and productive, it is vital to understand more about people's judgments of synergistic risks and how these judgments might be improved. From the findings presented in this thesis, it is possible to make recommendations that contribute to these goals.

First, it appears that there is some need to increase awareness of the synergistic risk concept and, in particular, of the potential for high synergistic risk magnitudes. Such awareness may increase the extent to which individuals and groups consider the likelihood of harmful synergies when making judgments concerning multiple hazards and reduce the extent to which individuals underestimate the likelihood of particular adverse events. This could also serve to counter the tendency, as identified in Chapters One and Two, towards believing that combined hazards are most likely to present additive risks. Second, concerted efforts should be made to disseminate evidence to all relevant parties (i.e., those potentially affected by the risk and/or those responsible for managing the risk) of the specific hazard combinations that have been found, in empirical studies, to present synergistic risks. As highlighted by the studies presented throughout this thesis, some individuals may be unaware of which specific hazard combinations present synergistic risks. Third, individuals' subjective risk judgments for combined hazards could be improved by risk messages that convey details of both the antecedent and probabilistic components of the synergistic risk concept and/or by encouraging individuals to develop greater judgmental experience concerning subjective risk assessments for combined hazards. Finally, a composed task format should be employed to assess pre- and post-intervention judgments of synergistic risks. As demonstrated in Chapter Three, this task format has shown good face, criterion and discriminant validity. Furthermore, the results presented in Chapter Four provide further support of the format's discriminant validity.

Limitations of the Present Research

There are a number of general limitations across the collection of studies presented in this thesis. First, the studies were based upon data obtained from convenience samples that were predominantly comprised of current university students or individuals who had previously attained qualifications at a university. Hence, the findings presented here may only be representative of 'highly educated' individuals (Beach et al., 1987). It would, therefore, be of great value to conduct further research in which more representative samples were employed and, ideally, which featured participants with a broader range of educational levels. Second, the research presented here has predominantly focussed upon subjective judgments of synergistic *health* risks. Although the results presented in Chapter One indicate that the hazard domain may not influence individuals' risk judgments for combined hazards, it should still be recognised that the results presented in this thesis may not be generalizable beyond the health domain. Hence, there is great scope for further research that investigates individuals understanding of the synergistic risk concept in non-health domains. Finally, the data gathered across all of the studies has been obtained in 'laboratory-style' conditions and using contrived 'pen-and-paper' judgment tasks. Consequently, the judgments made by the research participants may not have been representative of the more intuitive, heuristic-based judgments that individuals may typically make in more complex, rapidly evolving and naturalistic conditions (see Goodwin & Wright, 2004). Although this is, arguably, a substantial limitation to the generalizability of the results presented in this thesis, the present studies employed laboratory-style tasks for one important reason: in order to assess whether an individual understands that a hazard combination presents a synergistic risk, an empirical measurement must be obtained that indicates whether the individual believes that the risk presented by the hazard combination is greater than the sum of the risk presented by each of the constituent hazards operating individually. In other words, it is precisely because 'synergy' is a quantitatively defined concept that is was necessary to develop judgment tasks that forced participants to explicitly consider and/or produce quantitative risk estimates. Without such estimates, it would not have been possible to assess/calculate whether the participants had employed a sub-additive, additive or synergistic model of risk. However, it should also be noted that, in the development of the judgments tasks, several steps were taken to reduce/eliminate the extent to which the design of the tasks would elicit bias in the participants' judgments (see *Introduction and Background*). Nonetheless, future research could still aim to conduct studies in more naturalistic settings with the aim of assessing individuals' behavioural decisions in relation to hazard combinations that have been found to present synergistic risks.

Beyond the general limitations of the collection of studies presented in this thesis there are also specific limitations within some of the individual studies which are, in hindsight, worthy of consideration. First, the wording of the scenarios employed in Chapters One and Two featured some ambiguous wording which may have led the participants to misinterpret the question being asked. Specifically, within the scenarios, Statements One and Two did not explicitly indicate that the drug-user should be considered to be taking the stated drug (e.g., Drug A) *only*. Hence, participants could have inferred that the drug-user was taking the stated drug (e.g., Drug A) plus another drug (e.g., Drug B) or drugs as well. Second, Chapter Three employed samples that were recruited via the internet. Such sampling possess several advantages; for example, the lack of interaction between the experimenter and the participants can minimise 'experimenter/demand effects' (i.e., where the experimenters behaviour, either intentionally or unintentionally, provides the participants with subtle clues as to how the participants should respond to the experiment), and internet-sampling facilitates access to hard-to-reach populations and/or populations with diverse socio-demographic characteristics (Gosling, Vazire, Srivastava & John, 2004; Reips, 2000). However, internet-based can also suffer from some limitations that may have influenced the results obtained in the two studies presented in Chapter Three. For example, when using these internet samples it was not possible to detect whether one participant has participated twice or whether, contrary to the experimental instructions, a participant had consulted information sources before/during participation. Furthermore, it should be noted that the questionnaire for Study One, Chapter Three was available online for approximately three months. Thus, during this time period there may have been specific events (unknown to the experimenter) that could have influenced the participants who completed the questionnaire towards the end of this period to respond in a different way to the participants who completed the questionnaire at the very start of this period. Finally, a further specific limitation to Chapter Three relates to the extent to which the participant's confidence judgments are valid. In particular, research suggests that individuals' confidence judgments typically increase in 'overconfidence' (i.e., when confidence judgments are larger than the frequency of the correct answers) as the difficultly of the question(s) increase (Gigerenzer, Hoffrage & Kleinbolting, 1991). This 'easy-hard effect' may provide an explanation for the absence of a difference in the confidence judgments between each hazard combination in Study One of Chapter Three. That is, the question concerning the extent to which each participants was confident that his/her risk model judgment represented what had been found in scientific research may have simply been perceived as either an 'easy' or 'hard' question, irrespective of the hazard combination under consideration and, consequently, this may have resulted in a general pattern of overconfidence/underconfidence across all three combinations. Hence, the face validity of the confidence judgments may be somewhat questionable.

Future Directions

There appears to be an absence of studies that have examined whether veridical knowledge of synergistic risks influences risk-related behaviours. For example, it is unclear whether individuals who are aware of the multiple synergistic cancer risks attributable to smoking and drinking are any more likely to avoid or reduce these health-related behaviours than individuals who do not have such knowledge. Knowledge of the extent of this influence could prove extremely valuable to parties interested in understanding and predicting risk-related behaviours.

The results presented in this thesis provide little evidence to suggest that individuals employ sub-additive risk models for combined hazards. This finding could be considered reassuring, as it suggests individuals are not likely to make sub-additive risk estimates for synergistic hazard combinations. However, it should be noted that, in all of the studies presented here, participants did not make subjective risk assessments for hazard combinations that have been found, in scientific studies, to present sub-additive risks. Hence, there is considerable scope for future research to explore the risk models that individuals employ when assessing sub-additive risk combinations. Such investigations could explore, particularly for unfamiliar hazard combinations, whether individuals have a bias towards employing additive or weakly synergistic models of risk for most hazard combinations.

Another potential avenue for research in this area concerns assessing individuals' judgments of synergistic *benefits* (Chan, Mattiacci, Hwang, Shah, & Fong, 2000; Lui, 2003). For example, research shows that, for individuals who consume both fruit and vegetables, there is a synergistic reduction in the likelihood of developing certain health problems such as cancer, heart disease and strokes (Lui, 2003). Such research could provide further valuable insight into the psychological processes that are involved in subjective evaluations of the attributes of combined agents. In addition, research could specifically explore whether/how subjective risk judgments for combined hazards are affected by the presence of constituent hazards that are also judged to be beneficial (e.g., medicinal drugs, alcohol, etc.). Findings from such studies may provide important insights into the complex evaluations that people make regarding combined hazards and how these evaluations come to bear on their risk-related behaviours.

Finally, there is still extensive scope for conducting studies that make empirical assessments of the most effective and efficient ways of helping individuals to better understand synergistic risks. The focus of such studies could range from investigations concerning the effects of subtle variations in risk messages (e.g., frequency vs. percentage formats, animated vs. still images of antecedent mechanisms, etc.) to projects with the potential for much wider applications (e.g., developing a universal method/language for conveying details of synergistic risks that could be used on drug packets, food labels, risk assessment forms, investment briefings, etc.).

Conclusion

A vital skill for all individuals is the ability to make veridical judgments and effective decisions concerning risk. It is seldom the case that individuals have the time or resources to conduct lengthy research or employ formal decision analysis techniques that may enhance these risk-related judgments and decisions. Instead, individuals typically rely on their own, or even other people's, subjective risk assessments. When faced with judgments that involve combined hazards, these subjective assessments may not be veridical if the individual has failed to understand that the combination presents a synergistic risk. This could lead to severe or even fatal consequences. It is, therefore, somewhat reassuring that the evidence presented in this thesis indicates, in contrast to the findings from several previous studies, that many individuals can/do make veridical risk judgments for synergistic hazard combinations. However, it is important to note that the findings also show that such veridical judgments are not made by all individuals and that there appears to be subjective epistemic uncertainty regarding the risk attributable to certain synergistic hazard combinations. Furthermore, the findings also show that many individuals do not believe that specific hazard combinations present higher magnitudes of synergistic risk. These findings highlight the need to help individuals to better understand synergistic risks. It is, therefore, fortunate that the research findings presented in this thesis can be utilised to make substantial steps towards achieving this important objective.

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Appendices

Appendix One

Example Health Scenario:

Statement One: Scientific studies by Harris (2006, 2008) and Cox (2007, 2009) found that for people who use 'Drug C' once-a-day there is a side-effect of a 1 in a 100 chance of having a heart attack in any given year.

Statement Two: Scientific studies by Bodak (2006, 2008) and Carvill (2007, 2009) found that for people who use 'Drug D' once-a-day there is a side-effect of a 1 in a 100 chance of having a heart attack in any given year.

Statement Three: For people who use both 'Drug C' and 'Drug D' once a day there is a side-effect of a 20 in a 100 chance of having a heart attack in any given year.

Question 2: In consideration of the information in 'Statement One' and 'Statement Two', is it possible that 'Statement Three' is correct?

Yes ☐ No ☐

Example Social Scenario:

Statement One: Scientific studies by Warren (2006, 2008) and Liu (2007, 2009) found that male babies who suffer a difficult birth have a 1 in 100 chance of committing a violent crime before reaching adulthood.

Statement Two: Scientific studies by McKenna (2006, 2008) and Wilde (2007, 2009) found that male babies who are rejected by their mother in the first year of life have a 3 in 100 chance of committing a violent crime before reaching adulthood.

Statement Three: Male babies who suffer a difficult birth and are rejected by their mother in the first year of life have a 5 in 100 chance of committing a violent crime before reaching adulthood.

Question: In consideration of the information in ‘Statement One’ and ‘Statement Two’, is it possible that ‘Statement Three’ is correct?

Yes ☐ No ☐

Appendix Two

Example Scenario featuring a follow-up question that asked respondents to explain the reasoning that led them to judge that the scenario was possible/impossible:

Statement One: Scientific studies by Harris (2006, 2008) and Cox (2007, 2009) found that for people who use 'Drug C' once-a-day there is a side-effect of a 1 in a 100 chance of having a heart attack in any given year.

Statement Two: Scientific studies by Bodak (2006, 2008) and Carvill (2007, 2009) found that for people who use 'Drug D' once-a-day there is a side-effect of a 1 in a 100 chance of having a heart attack in any given year.

Statement Three: For people who use both 'Drug C' and 'Drug D' once a day there is a side-effect of a 20 in a 100 chance of having a heart attack in any given year.

Question 1: In consideration of the information in 'Statement One' and 'Statement Two', is it possible that 'Statement Three' is correct?

Yes	☐	Go to Question 1(a)
No	☐	Go to Question 1(b)

Question 1(a): Please explain why the circumstances described in 'Statement Three' could occur: .... [free text field]

Question 1(b): Please explain why the circumstances described in 'Statement Three' could not occur: .... [free text field]

Appendix Three

Example judgment task featuring the aspirin-clopidogrel combination in a numeric frame:

Read the paragraph below and respond to the task by ticking one of the boxes.

Research evidence shows that a person who takes a low-dose of ‘aspirin’ each day has a 100 in 100,000 chance of suffering gastro-intestinal bleeding in any given year. Research evidence also shows that a person who takes a low-dose of the antiplatelet drug ‘clopidogrel’ each day has a 10 in 100,000 chance of suffering gastro-intestinal bleeding in any given year.

Judgment task: Please now consider the chance of a person suffering gastro-intestinal bleeding in any given year if they take a low-dose of aspirin each day **and** a low-dose of clopidogrel each day.

Do you judge the chance as being either **less than**, **equal to**, or **more than** ‘the chance of gastro-intestinal bleeding for a person who takes low-dose aspirin each day’ **added to** ‘the chance of gastro-intestinal bleeding for a person who takes low-dose clopidogrel each day’?

Less than ☐

Equal to ☐

More than ☐

Example judgment task featuring the radon-tobacco combination in a verbal frame:

Read the paragraph below and respond to the task by ticking one of the boxes.

Research evidence shows that a person who lives in a dwelling for 30-years where there is a high level of radon (a naturally occurring radioactive gas) has an increased chance of developing lung cancer during their lifetime. Research evidence also shows that a person who smokes 20 cigarettes per-day throughout adulthood has an increased chance of developing lung cancer during their lifetime.

Judgment task: Please now consider the chance of a person developing lung cancer if that person lives in a dwelling for 30-years where there is a high level of radon **and** that person smokes 20 cigarettes per-day throughout adulthood.

Do you judge the chance as being either **less than**, **equal to**, or **more than** 'the chance of developing lung cancer for a person who lives in a dwelling for 30-years where there is a high level of radon' **added to** 'the chance of developing lung cancer for a person who smokes 20 cigarettes per-day throughout adulthood'?

Less than ☐

Equal to ☐

More than ☐

Example judgment task featuring the alcohol-driving combination in a numeric frame:

Read the paragraph below and respond to the task by ticking one of the boxes.

Research evidence shows that a person who drives a vehicle on a road (on an average number of occasions) has a 3 in 100,000 chance of being killed in a road accident in any given year. Research evidence also shows that a person who becomes intoxicated by alcohol (on an average number of occasions) has a 1 in 100,000 chance of being killed in a non-road accident in any given year.

Judgment task: Please now consider the chance of a person being killed in an accident if that person drives a vehicle on a road (an average number of times) **and** they are intoxicated by alcohol on each occasion.

Do you judge the chance as being either **less than**, **equal to**, or **more than** 'the chance of being killed in an accident for a person who drives a vehicle on a road' **added to** 'the chance of being killed in an accident for a person intoxicated by alcohol'?

Less than ☐

Equal to ☐

More than ☐

Appendix Four

Judgment tasks employed in study reported in Chapter Four:

Please read the paragraph below and respond to the tasks.

Research evidence shows that a person who is a heavy smoker has a 2 in 100 chance of developing esophageal cancer during their lifetime. Research evidence also shows that a person who is a heavy drinker has a 6 in 100 chance of developing esophageal cancer during their lifetime.

Task One: Please now consider the chance of a person developing esophageal cancer during their lifetime if they are both a heavy smoker **and** a heavy drinker.

Do you judge the chance as being either **less than**, **equal to**, or **more than** 'the chance of developing esophageal cancer for a heavy smoker' **added to** 'the chance of developing esophageal cancer for a heavy drinker'?

Less than ☐

Equal to ☐

More than ☐

Task Two: Please answer the following questions:

Out of a population of 100 people, each of whom is a heavy smoker **and** a heavy drinker, how many of them do you estimate will develop esophageal cancer during their lifetime?

Answer: ____ out of 100.

Appendix Five

Numeracy scale employed in study reported in Chapter Four:

You will now be asked to answer 8 questions. Here is an example:

Example question: Imagine that a fair coin is tossed 1,000 times. What is your best guess about how many times the coin would come up heads in 1,000 flips?

Answer: 500

Please now answer the following 8 questions:

1. Which of the following numbers represents the biggest risk of getting a disease?

___ 1 in 100, ___ 1 in 1000, ___ 1 in 10

2. Which of the following numbers represents the biggest risk of getting a disease?

___ 1%, ___ 10%, ___ 5%

3. If Person A's risk of getting a disease is 1% in ten years, and person B's risk is double that of A's, what is B's risk? ___ %

4. If Person A's chance of getting a disease is 1 in 100 in ten years, and person B's risk is double that of A's, what is B's risk? _______________

5. If the chance of getting a disease is 10%, how many people would be expected to get the disease:

- out of 100? ___
- out of 1000? ___

6. If the chance of getting a disease is 20 out of 100, this would be the same as having a ____% chance of getting the disease.

7. The chance of getting a viral infection is .0005. Out of 10,000 people, about how many of them are expected to get infected? ____

8. In a sweepstake, the chance of winning a car is 1 in 1,000. What percent of tickets in this sweepstake win a car? _____