Web Appendix

The model description follows the ODD+D protocol (Müller *et al.*, 2013), based on the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm *et al.*, 2006, 2020).

A.1 The ODD+D for the ABM model of a risk workshop.

Outline		Guiding questions	ODD+D Model description
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?	The study builds upon Harten *et al.* (2022), which is a theoretical exploration of the drivers of the effectiveness of risk assessments in risk workshops regarding the correctness and required time. Harten *et al.* (2022) model agent's cognition using Bayesian networks. We argue that their modeling choice corresponds well to an organizational environment where a calculative culture of quantitative enthusiasm is prevalent. The purpose of our paper is to investigate the impact of calculative cultures on risk workshops. More specifically, we explore drivers of the effectiveness of risk assessments in risk workshops dominated by 'quantitative skepticism' and contrast our findings with previous research that assumed the dominance of 'quantitative enthusiasm.' To this end, we adapt their model to a setting that better corresponds to an environment where quantitative skepticism is prevalent. We, therefore, chose constraint satisfaction networks. Specifically, we use ECHO networks (Thagard, 1989) with a similar structure to the Bayesian networks used by Harten *et al.* (2022) to model agents' cognitive processes. In order to be able to compare results with Harten *et al.* (2022), we perform the same experiments as described in the original paper and the corresponding ODD (available at Harten *et al.*, 2021). Specifically, we model the limits to information transfer, incomplete discussions, group characteristics, and interaction patterns and investigate their effect on risk assessment in risk workshops.

		I.ii.b For whom is the model designed?	The model ideally guides facilitators of risk workshops in understanding the design choices and trade-offs they face, especially the importance of the prevalent calculative culture for accounting and design-related decisions. The model also provides a blueprint to use ABM to simulate organization discussion processes.
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	This ABM has nine agents, all of whom are participants in a risk workshop. In each simulation run, one risk task is generated in the form of a constraint satisfaction network. The participants perform a discussion, during which they exchange information about the risk. During the discussion, one agent (chosen at random) takes a special role as a leader, in addition to the role as a participant. Additionally, a facilitator's role is needed during the discussion process. However, - as we detail later - the role of the facilitator only requires information available to all participants or any external observer; the role of the facilitator is not implemented as an agent entity itself but only as a function. Overall, the following entities are present in the model: <u>Risk workshop participants</u> who discuss a risk in order to reach a correct risk assessment; <u>a leader</u> who is one of the participants in the risk workshop but is responsible for making the final decision; <u>a facilitator</u>, who makes decisions regarding the proceeding of the workshop (Should the discussion continue, or a decision be made? Who is the next participant to speak?); <u>a risk</u>, modeled as a constraint satisfaction network that is assessed in the risk workshop.

		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized?	Risk workshop participants (including the leader) are characterized by three attributes: <u>Initial information concerning the risk</u>: Participants are provided with some information about the risk during the initialization. The pool of information that is assigned to the participants corresponds to the information nodes in the figure below. If participants are provided information, they integrate the corresponding information node into their constraint satisfaction network. Participants are considered experts regarding the information they are initially provided. <u>Knowledge of the risk structure</u>: Participants have a constraint satisfaction network as their mental model of the risk. The constraint satisfaction network (Thagard, 1989) of the participants is initially limited, as some information nodes and their relationship to other nodes are missing. After participants receive new information, they update their individual constraint satisfaction network by adding new nodes and their relationships with the nodes already in their network (either explanatory or contradictory). <u>Level of hierarchy</u>: Participants are randomly assigned to one of three levels of hierarchy: low, medium, or high. There are always three participants for each level of the hierarchy. The leader is randomly chosen from the participants with a high level of hierarchy. The risk under assessment is characterized by the relationships between the nodes of the full constraint satisfaction network. A risk is a constraint satisfaction network with two nodes representing the risk assessments “low likelihood risk” and “high likelihood risks” and nodes representing nine issues and 27 information. Each node has an activation in the range between -1 and 1, representing the strength of belief in the corresponding node. The activation changes depending on

			the relationship of the nodes with each other. This (symmetric) relationship is either explanatory or contradictory (or there is no direct relationship at all). For example, a piece of specific information ("a new competitor enters the market with a similar product") might have an explanatory relationship with one issue ("the market we operate in is attractive") node and a contradictory relationship with another issue node ("we have a technological lead in the market"). Figure 1: The structure of the Bayesian network used by Harten *et al.* (2022) (left) and the stylized ECHO network used to model quantitative skepticism (right). The benchmark risk assessment is derived from the activation of the two risk assessment nodes depicted at the top when all information nodes are provided instantly (e.g., the risk assessment of an agent with access to the whole constraint satisfaction network from the beginning).
		I.ii.c What are the exogenous factors / drivers of the model?	Several simulation experiments are conducted with the model. Depending on the experiment, the following attributes are systematically varied: • Initial distribution of information among the risk workshop participants: Either all participants get the same amount of information, or information is

			assigned unequally. Specifically, each information from the pool of information that is initially assigned to the group is distributed one after another. For each information, each participant has a specific probability of receiving this information. If information is distributed equally, each agent's probability of receiving a piece of specific information is 11.1% (i.e., 100%/9). Otherwise, the probabilities are chosen so that the best-informed participant has twice the chance of receiving any information as the second-best informed participant (factor 2), and so on. Participants are chosen at random regarding their place in the knowledge distribution (i.e., if they are more or less well informed). • Decision rules used by the leader to make decisions • Consideration of hierarchy by the participants: Participants can weigh decisions higher or lower, depending on the position of the sender in the hierarchy relative to their own. • Presence of transactive memory within the group: If transactive memory is present, participants know if the sender is an expert in the information being sent and can weigh the input higher or lower (depending on their expertise). • Interaction pattern within the group
		I.ii.d If applicable, how is space included in the model?	Space is not included in the model.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	One time step is one discussion round, meaning that a participant is chosen to speak, the speaker provides a piece of information, and all other participants process it. See Figure 2 for the steps that happen during one simulated risk workshop.

	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	 Figure 2: Stages of the simulation before, during, and after the risk workshop (adapted from Harten *et al.*, 2022).

II) Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?	The model has been developed to investigate the impact of choices made during the facilitation of a risk workshop, given a calculative culture of quantitative skepticism (Mikes, 2009). While some results are specific to decision-making regarding risk assessment, the general concept can be transferred to other settings where a group shares distributed knowledge in a discussion to make a decision. The interaction of the participants is built upon the idea of participants forming a transactive memory system (Wegner, 1987); all relevant information for a decision is available to the group, but the group needs to make use of the available information correctly. The experiments investigate deviations from an ideal speech situation (Habermas, 1982), as discussed in Harten *et al.* (2022).
		II.i.b On what assumptions is/are the agents' decision model(s) based?	The participants' decisions are based on heuristics that aim to reasonably account for all available information relevant to the respective decision. The participants are either following simple mathematical formulas for their decisions (e.g., when the leader determines if the discussion should continue), or make random choices, where model parameters determine the probability of each option to be chosen (e.g., when participants decide what information to share with the others).
		II.i.c Why is a/are certain decision model(s) chosen?	For some settings, there are no clear-cut rules available for how our participants will decide to act during the discussion. Thus, when participants need to make decisions, we allow participants to choose randomly between all possible options (e.g., when they decide who should be the next sender). However, the probability of each choice is influenced by reasonable heuristics (e.g., when the group is aware of the hierarchy, the facilitator should be more likely to choose agents with a high position in the hierarchy as the following senders).

		II.i.d If the model / a submodel (e.g., the decision model) is based on empirical data, where does the data come from?	The model is not based on empirical data.
		II.i.e At which level of aggregation were the data available?	Not applicable.
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modeled? Are multiple levels of decision making included?	Participants make two types of decisions: If they are chosen to be senders in a given discussion round. They choose what information to talk about. If they are chosen to be receivers, they decide how to weigh the input they receive from the sender. The facilitator makes one specific decision: In each round, one participant is chosen by the facilitator to be the next sender. The leader makes two specific decisions: After each round, the leader decides if the conditions for the decision and termination approaches are met, and therefore, a decision can be made. The leader also makes the final decision on how to assess the risk. The objective of the leader is to reach an accurate risk assessment in the shortest possible time. However, the criteria to end the discussion is not determined by the leader but is a model parameter. The leader might decide to end the discussion and make a decision if the group has not progressed for some time.
		II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Participants make their best effort to gain a correct understanding of the risk in order to reach an accurate risk assessment. They have no hidden agendas or other individual objectives.

		II.ii.c How do agents make their decisions?	Participants make their decisions by random choice; however, the probability of each decision might not be equal. For example, participants are more likely to talk about information they are experts on.
		II.ii.d Do the agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how?	Agents do not adapt their behavior.
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	The selection of the next sender is influenced by social norms (e.g., prioritize participants based on hierarchy) in some experimental settings.
		II.ii.f Do spatial aspects play a role in the decision process?	Not applicable.
		II.ii.g Do temporal aspects play a role in the decision process?	The leader might decide to end the discussion and make a decision if the group has not progressed for some time.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	The participants can take uncertainty regarding the correct risk assessment into account, e.g., when the facilitator chooses the next sender.
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	The agents' understanding of the risk under assessment is modeled as an individual constraint satisfaction network for each agent. Participants update their understanding of the risk, based on the input they receive during the discussion from other participants. Their understanding of the risk determines their individual risk assessment. They do not learn beyond the discussion of an

			individual risk, i.e., there is no interaction spanning several simulated discussions.
		II.iii.b Is collective learning implemented in the model?	By exchanging their individual knowledge, the participants' understandings of the risk may move towards a more common understanding.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	Not applicable.
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	In some experimental conditions, participants know other participants' relative position in the hierarchy and other participants' expertise. This knowledge, if available, is free of errors. The facilitator and the leader know the overall risk assessment of all participants and can choose the next sender and decide when to end the discussion based on this knowledge.
		II.iv.c What is the spatial scale of sensing?	Not applicable.
		II.iv.d Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?	Participants are assumed to know variables like the expertise of other participants (if the corresponding experimental condition is present). Participants learn about other participant's understanding of the risk via the simulated discussion.
		II.iv.e Are costs for cognition and costs for	The cost of cognition and information gathering is accounted for by the fact that the leader makes a decision as soon as specific decision and termination criteria are met, instead of continuing the discussion potentially infinitely. However,

		gathering information included in the model?	the participants make no conscious decision on whether to invest cognitive resources: whenever they get new input, they update their knowledge about the risk and their risk assessment.
	II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Participants do not predict future conditions.
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	Not applicable.
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	Not applicable.
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	The participants directly interact with each other by exchanging information about the risk during the discussion.
		II.vi.b On what do the interactions depend?	In each discussion round, one participant is chosen to talk to all other participants. The other participants are only receivers in that discussion round but can become senders themselves in subsequent rounds.
		II.vi.c If the interactions involve communication, how are such communications represented?	Participants communicate by exchanging information about their individual knowledge about the risk. Usually, they will share the activation of their information node (“their knowledge”) they have decided to share. The agents will deduct themselves how the new information relates to nodes already in their network. This process is assumed to be objective, i.e., all agents will agree if two nodes are in an explanatory or contradictory relationship.

		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	The setting for the simulation is one discussion by all participants. Therefore, each participant can send information to all other participants, if chosen to be the sender.
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	The individual participants form a group. The risk assessments of the individuals can be aggregated to a decision, like a consensus, a majority vote, or an average vote (used to determine if the group opinion is moving over time). The leader decides to end the discussion based on such aggregates.
		II.vii.b How are collectives represented?	The collective (that is, the group of all participants) has no agency by itself and is only a conceptual component of the model. All decisions are made by individual participants.
	II.viii Heterogeneity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	The group participants differ in their initial knowledge and expertise. They might differ regarding their position in a hierarchy if the corresponding experimental condition is present. The participants have heterogeneous mental models initially, as the risk structure of their mental models depends on the information provided to them.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or	Agents are not heterogeneous in their decision-making.

		decision objects differ between the agents?	
	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?	For each run, a randomly generated risk is chosen for the group to assess. The decision by the facilitator of who is the next sender in a discussion round is random. Depending on experimental settings, the probability of each participant becoming the next sender can be unequal (e.g., when priority is given to some participants based on their risk assessment). The decision by the sender on what to share is random. The probability of each node being chosen for sharing can be unequal, depending on experimental settings.
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected?	At the beginning of each run, the independent variables are recorded. After each discussion round, the activation of all states of the 'overall assessment' node is recorded for each participant. Furthermore, it is checked and recorded if a decision and termination rule has been activated during the most recent discussion round and what decision by the leader it would result in.
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)	We can observe how limitations to the ideal speech situation impact the effectiveness of risk workshops, measured as the share of high and low risks that get assessed correctly, as well as the time it takes to make a decision.
III) Details	II.i Implementation Details	III.i.a How has the model been implemented?	The simulation is entirely written in Python. The original ECHO code was reimplemented in Python for this study.
		III.i.b Is the model accessible and if so where?	The model will be published on the OpenABM platform.

	III.ii Initialization	III.ii.a What is the initial state of the model world, i.e., at time t=0 of a simulation run?	<u>The benchmark assessment and the benchmark process</u> The simulation requires a benchmark assessment that the assessments reached in the risk workshop can be compared against. The benchmark assessment is determined by calculating a constraint satisfaction network with full information about the true risk. This is the assessment that an agent would reach if all information relevant to the risk assessment were available from the beginning. <u>Initial information distribution</u> In the beginning, information concerning the risk is distributed to the participants. After this initial seeding of (true) information, participants only get new input from other participants. All participants are able to assess the overall risk based on the limited knowledge they are pro-vided initially. Each information about the risk is available to at least one participant, so a correct risk assessment would be achieved if all participants could ideally share their information. The 27 pieces of information are distributed among the participants, either equally or unequally. <u>Knowledge about each other's hierarchical position</u> Each participant is assigned a specific hierarchical status (low, medium, high). If the corresponding experimental condition is present, participants are aware of the hierarchical status of the other participants and consider it when including sender input into their individual constraint satisfaction network. <u>Knowledge about each other's expertise</u> Information provided to the participants initially constitutes their expertise regarding the risk. Depending on the experimental condition, participants might be informed about each other's expertise, i.e., who is an expert concerning which information.

		III.ii.b Is initialization always the same, or is it allowed to vary among simulations?	Several simulation experiments are conducted with the model. Depending on the experiment, the following attributes are systematically varied: <u>Initial distribution of information among the risk workshop participants</u>: Either all participants get the same amount of information, or information is assigned unequally. Each information from the pool of information that is initially assigned to the group is distributed one after another. For each information, each participant has a specific probability of receiving this information. If information is distributed equally, each agent's probability of receiving a piece of specific information is 11.1% (i.e., 100%/9). Otherwise, the probabilities are chosen so that the best-informed participant has twice the chance of receiving any information as the second-best informed participant (factor 2), and so on. Participants are chosen at random regarding their place in the knowledge distribution (i.e., if they are more or less well informed). <u>Consideration of hierarchy by the participants</u>: Participants can weigh decisions higher or lower, depending on the position of the sender in the hierarchy relative to their own. <u>Presence of transactive memory within the group</u>: If transactive memory is present, participants know if the sender is an expert in the information being sent and can weigh the input higher or lower (depending on their expertise).
		III.ii.c Are the initial values chosen arbitrarily or based on data?	The initial values are chosen arbitrarily, within the constraints set by the model parameter.
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent	Not applicable.

		processes that change over time?	
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	<u>Sender selection</u> The facilitator chooses the sender in a random draw that depends on the experimental condition. Only agents who have any expertise in any node are eligible to become senders, as otherwise the sender has no information to share. The following interaction pattern are investigated: Random: In the baseline model, the next participant to speak is chosen at random, with an equal probability for each participant. Priority is given to concern: The probability of each participant to be chosen is weighted by their overall risk assessment. Priority is given to dissent: The probability of each participant to be chosen is weighted by the distance of their individual risk assessment from the average group risk assessment. Priority is given to hierarchy: Participants are more likely to be the sender if they are assigned a higher hierarchical position. The probability of each participant to be chosen is weighted by *weight_h_low*, *weight_h_medium*, or *weight_h_high*. Priority is given to homogeneity: The probability of being the next sender is higher if the participant's risk assessment is close to the average group risk assessment. <u>Selection of sender output</u> The senders chose one of the information nodes available to them. The chance of choosing a specific node is weighted by the sender's expertise regarding the information node. The expertise is *weight_e_expert* for nodes initially assigned to the sender and *weight_e_nonexpert* for all other nodes. The sender will

			provide the detailed state of the information node to all other participants, who are the receivers in the given round. Furthermore, participants prioritize talking about nodes that have not been discussed often. The previously determined weight for each node ($node_i$) based on the participant's expertise regarding the node is multiplied by a weight reflecting how much it has been talked about by the group already, relative to the node that was talked about most often ($node_{max}$): $weight(node_i) = weightExp(node_i) * 2^{discussionCounter(node_{max}) - discussionCounter(node_i)}$ Here, *weightExp($node_i$)* is either *weight_e_expert* if the sender is an expert on $node_i$or *weight_e_nonexpert* otherwise. $discussionCounte(node_i)$ gives the number of times $nodei$ has already been discussed in this simulation run. <u>Inclusion of sender input</u> All receivers update their beliefs about the node the sender talks about by assigning the input a weight relative to their prior belief. Depending on the experimental condition, the weight assigned to the input reflects the following aspects: • difference in expertise regarding the specific node between sender and receiver; • difference in hierarchy between sender and receiver. For example, the receiver will weigh the input higher if the sender is an expert and the receiver is not, or if the sender has a higher position in the hierarchy than the receiver. For example, if a non-expert assessed the activation of an information node to as 0 and received the information of an expert that assesses the activation to be 0.23, the updated belief of the non-expert will be $0.23 * (\text{weight_e_expert} - \text{weight_e_nonexpert}) - 0.0 * (1 - (\text{weight_e_expert} - \text{weight_e_nonexpert}))$

		III.iv.b What are the model parameters, their dimensions and reference values?	See A.2
		III.iv.c How were submodels designed or chosen, and how were they parameterized and then tested?	The submodels were designed to reflect a prototypical implementation of the processes during a risk workshop. The experimental conditions were derived by Harten *et al.* (2022) as deviations from an ideal speech situation and implemented as simply as possible. All decisions made by agents are either random or influenced by simple heuristics.

A.2 Parameters of the model.

Parameter	Explanation	Default value(s)
nr_agents	Number of participants	9
threshold_change_continue	Maximum deviation in the group risk assessment for the discussion to be considered stagnant.	0.01
Risk model		
nr_issue_nodes	Number of children each parent-node has in the reference risk network	3
connectedness_issues	Probability that two issue nodes are connected by a constraint to each other	0.2
connectedness_information	Probability that an information node and an issue node are connected by a constraint to each other	0.2
connectedness_assessment	Probability that an issue node and a risk assessment node are connected by a constraint to each other	0.4
connections_rate_explanatory	Probability that a constraint is explanatory, rather than contradictory	0.6
Experimental conditions		
information_distribution	Determines whether all agents have the same probability to receive an information in the initial distribution	equal / unequal
weight_hierarchy	Participants consider the difference in hierarchy when weighting sender input	yes/no
weight_trans_mem	Participants consider the difference in expertise when weighting sender input	yes/no
mode_limited_trans	Participants consider their prior belief when integrating new information	yes/no
decision_rule	Decision-making rule used by the leader	
Interaction_pattern	Interaction pattern used in the group	

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