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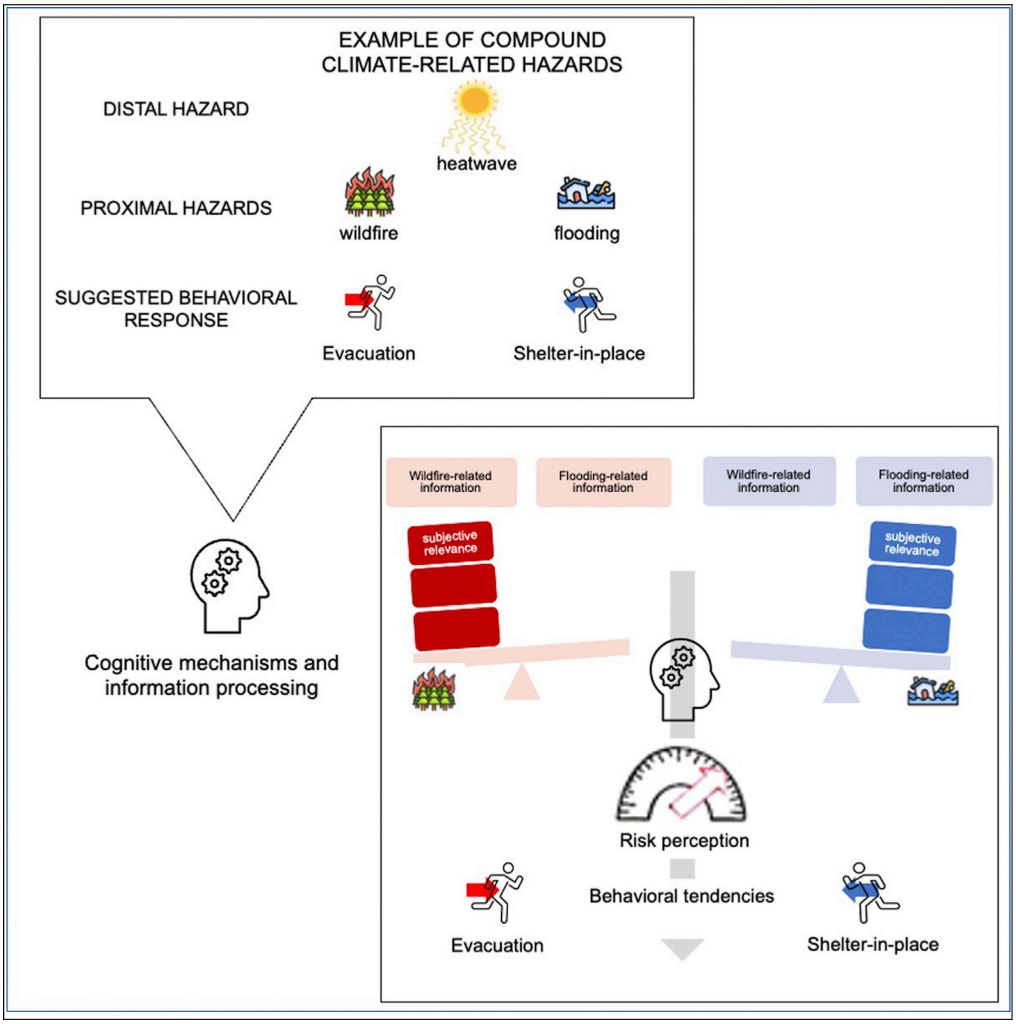

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Highlights

Risk perception in case of compound events might be impaired by cognitive mechanisms

Facing complex configurations, individuals attribute relevance to specific causal cues

Subjective attribution of relevance to specific cues tailors environmental risk perception

Subjective attribution of relevance to specific cues influences behavioral tendencies

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Risk perception and behavioral intentions in facing compound climate-related hazards

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SUMMARY

Compound climate-related events are a complex combination of climate drivers and hazards leading to a significant impact on natural and anthropic systems. Owing to their complexity and critical consequences, interdisciplinary undertaking is required to improve risk analysis, management, and communication. Although prior research in cognitive sciences extensively investigated risk perception in case of a single hazard, the analysis of compound hazards perception is still an open issue. Here, based on cognitive psychology insights, we empirically investigate how individuals' risk perception is shaped by the subjective relevance attributed to different causal cues entailed in a compound event scenario. The results revealed that the subjective validity assigned to specific evidence presented in the composite scenario leads perceived risk related to one of the outcomes (i.e., flooding and wildfire) to prevail over the other. Moreover, the relevance of different cues is likely to affect participants' automatic behavioral intentions (stay at home vs. evacuation).

INTRODUCTION

Compound climate-related events are complex manifestations of natural hazards, characterized by the interactions of various physical processes across multiple spatial and temporal scales, generated by meteorological variables, and provoking extreme impacts.[1-3] Compound climate-related event studies have shown how often the natural hazards occur connected to each other and the importance of considering these connections for a proper evaluation of risk.[4,5] Climate change may influence the risk associated with these events, exacerbating the impacts, altering their likelihood, and the local and worldwide patterns.[6] In the light of climate change's global negative consequences, it is even more essential to further improve climate and risk estimation models to support risk management policies and address the increasing human and economic losses due to (compound) natural disasters.[7]

Zscheischler and colleagues[8] proposed a categorization of compound climate-related events in four distinct typologies: (1) preconditioned events refer to a situation where a climate (or weather) background precondition can enhance the impact triggered by one or more hazards; (2) multivariate events can result in impacts due to concurrent drivers and/or hazards at about the same location; (3) temporally compounding events, which can lead to impacts due to a sequence of drivers and/or hazards; and (4) spatially compounding events, which can lead to aggregated impacts as a result of drivers and/or hazards occurring in multiple connected locations. This categorization is important to show the variety and complexity of situations with which compound events may occur. Although investigating occurrence, properties, and interdependencies of compound climate-related hazards is an urgent challenge for engineering and environmental sciences, an extensive understanding of the phenomenon and its impact also requires the integration of cognitive and behavioral sciences perspective.

Indeed, in anthropic environments, risk results from the interplay of hazard, exposure, and vulnerability.[9,10] Exposure and vulnerability, which play a critical role in the final impact of a natural disaster, are primarily determined by the human factor.[11] Where, when, and which populations are exposed to compound climate-related events are all strong predictors of the severity of impacts; thus, anthropic systems interact with the natural environment to direct and shape the ultimate impacts of such events. For this reason, a more psychologically grounded account of the effects of human precautionary behavior is crucial to improve models of risk estimation. In this vein, prior psychological research has already shown a clear relation between risk and various psychological factors, such as perceived risk, perceived response efficacy,

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self-efficacy, feelings of worry, and preparedness toward several types of hazards.[12-14] Among these different factors, risk perception and its deviations from actual risk represent a critical process to understand inhabitants' behavioral reactions to natural hazards.[15,16]

Although prior research extensively investigated risk perception and consequent behavioral responses in case of a single hazard,[12] the analysis of compound hazards perception is an open issue and requires investigation. Indeed, in such conditions, individuals and groups have to identify and cognitively combine information about simultaneous hazards and effects within configural patterns. For decades, cognitive psychology highlighted a series of heuristics and systematic distortions that intervene on people's inductive reasoning, subjective probability assessment, and causal inference,[17,18] thus being potentially critical in compound events perception and interpretation. For instance, such biases in intuitive judgment of probability lead people to ignore the base-rate frequency of an event (*base-rate fallacy*[19]), neglect information on the sample size or misconceive the concept of chance,[20] and find order and relationships between uncorrelated values (*illusory correlations*[21,22]). In addition, a large strand of research analyzed psychological mechanisms affecting covariation perception and causal reasoning, ranging from associative processes related to events' perceptual characteristics and temporal contiguity to preexisting individuals' knowledge-based mental models.[23]

The scenario is further complicated when the decision-maker needs to deal with multiple potential hazards or target effects. In cognitive psychology, there is an extensive debate lasting several decades[24-27] around the so-called *conjunction fallacy*, claiming that subjective probabilities of compound events (A & B) are systematically biased in the direction of their components, resulting in overestimation of the likelihoods of conjunctive events (A ¬B or ¬A B). Furthermore, in case of compound climate-related events, the perceiver has to deal not only with the conjunction of events but also with a complex causal pattern involving multiple predictors.[28] In such a condition, without adequate knowledge on the statistical structure of information in a particular environment, people tend to use fast-and-frugal cognitive strategies and heuristics (in particular, under time pressure, that is a common condition in case of natural disaster). Specifically, the literature underlined that, when multiple antecedents of an effect are available, people are more prone to use a single relevant cue than the compound, even if the validity of the compound is higher than the validity of the individual cue.[29] In particular, individuals generally use the antecedent with the highest subjective validity as a cause to explain an event or constrain the number of cue combinations to a subset they consider highly predictive. In fact, since the "configural information processing" (i.e., the integration of different cues) requires extra cognitive effort, individuals use their naïve causal knowledge about the cues predictivity to simplify the process and save cognitive resources.[28] Overall, the mentioned research in cognitive psychology highlighted a series of psychological mechanisms likely to forge risk perception when multiple events occur simultaneously or in a cascading manner.

Based on these empirical insights, the present work aims to contribute to filling the gap in scientific understanding of risk perception in case of compound climate-related events. More specifically, the research focused on a definite scenario in which multiple hazards and outcomes are implicated. The main goal of the study is to investigate whether, in such a condition, individuals are prone to assign priority to some data, rather than adopting an accurate configural information processing. To this aim, we explored if the subjective importance of casual cues is predictive of the perceived general hazard. Then, we tested whether the relevance assigned to some specific causal cues affects risk perception of corresponding disastrous events. In line with the cited literature, we hypothesized that, in facing compound events, individuals would attribute more importance to some causal cues (e.g., some data or information on specific facets of the compound) than others. Consequently, the perceived risk associated to that favored single event would increase, if compared to other negative events comprised in the compound (Hypothesis 1). In other terms, risk perception is shaped by the subjective relevance attributed to specific causal cues. Moreover, the study intends to explore if and how hazard perception in such a complex condition is likely to tailor the following behavioral responses.[9] Thus, we investigated the relation between perception of cue relevance in risk estimation and anticipated behaviors. In line with the previous hypothesis, we anticipate that the importance attributed to some specific casual cues is predictive of the preference for a behavioral response, more explicitly the behavior associated with a specific single negative event in the compound (Hypothesis 2). To investigate this hypothesis, a dilemmatic scenario was considered, where different risk profiles lead to competing behavioral alternatives.

Therefore, to investigate risk perception and behavioral intentions in a compound climate-related event, a survey has been designed and delivered to participants (a sample of 198 Italian adults). Risk perception and

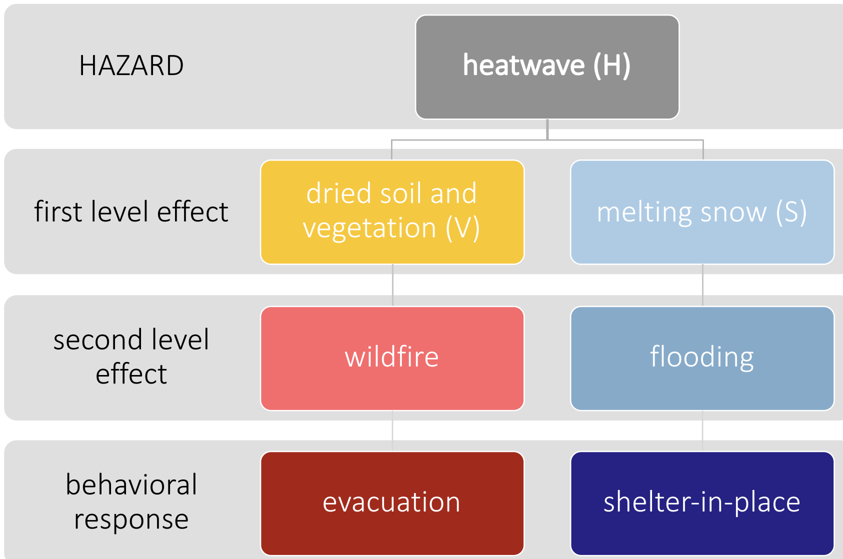

Figure 1. Scenario structure

Structure of the scenario describing connected extreme events and proper behavioral responses associated with negative outcomes.

preparedness behaviors have been explored at the household level. Participants were presented with a fictitious scenario representing a compound climate-related event; in particular, a multivariate event has been chosen with cascading hazards (see Figure 1). Then, the participants were asked to identify with a person involved in that situation. Other scenarios might be considered for the other typologies of compound events. Here, the scenario has been inspired by the events that occurred along the Pacific coast of the U.S. and Canada during summer 2021.[30] The scenario described a case of a heat wave (i.e., hazard) that dried the vegetation and the soil (i.e., first-level $effect_A$) and, at the same time, accelerated snow melting (i.e., first-level $effect_B$). Consequently, the region was threatened by diffused wildfires (i.e., second-level $effect_A$ and a cascading hazard) and critical increase of the river water level with floodings (i.e., second-level $effect_B$ and a cascading hazard). The scenario also provided information on the appropriate but competing behavioral responses toward the two second-level effects: evacuation in case of fire (i.e., behavioral $response_A$) and shelter-in-place in case of flooding (i.e., behavioral $response_B$). Therefore, in line with our goals, the scenario implies multiple connected hazards and a behavioral dilemma. Although the real experience is not necessarily characterized by a dilemmatic situation (i.e., the second-level effects might lead to congruent responses), this structure of the decisional scenario allows an accurate analysis of the relation between perceived information relevance and behavioral consequences. Moreover, it might have relevant implications since a response to a risk (e.g., evacuation in case of fire) is likely to increase exposure to the risk associated with a second hazard (e.g., flood) and vice versa.

After reading the scenario, to explore cognitive accessibility of evacuation vs. shelter-in-place thoughts, participants were presented with a lexical decision task (LDT; see Figure 2). The LDT[31,32] is widely used in cognitive psychology experiments as a measure of semantic accessibility. Specifically, the present LDT explored the facilitation of thoughts related to the two opposite behavioral alternatives (staying at home vs. evacuating). Participants were presented with words related to the outside (e.g., outdoor), words related to the inside (e.g., indoor), and nonwords (e.g., donrio) and asked to classify each letter string as a word or a nonword. Participants' reaction times (RTs) in classifying words related to the outside (vs. inside) were recorded. Indeed, the elapsed time between the sensory stimulus onsets (i.e., word presentation) and subsequent behavioral responses is an index of information processing: faster RTs in a stimulus categorization indicate facilitation and higher cognitive accessibility (see method details). In the LDT, participants are consciously exposed to the stimuli (words) but unaware that the specific cue has an effect on their behavior (response). Thus, this implicit measure allows to evaluate automatic processes that are not under the individual's cognitive control. Automatic processes, different from controlled and deliberative ones, are fast, effortless, involuntary, and unavailable to conscious awareness.[33]

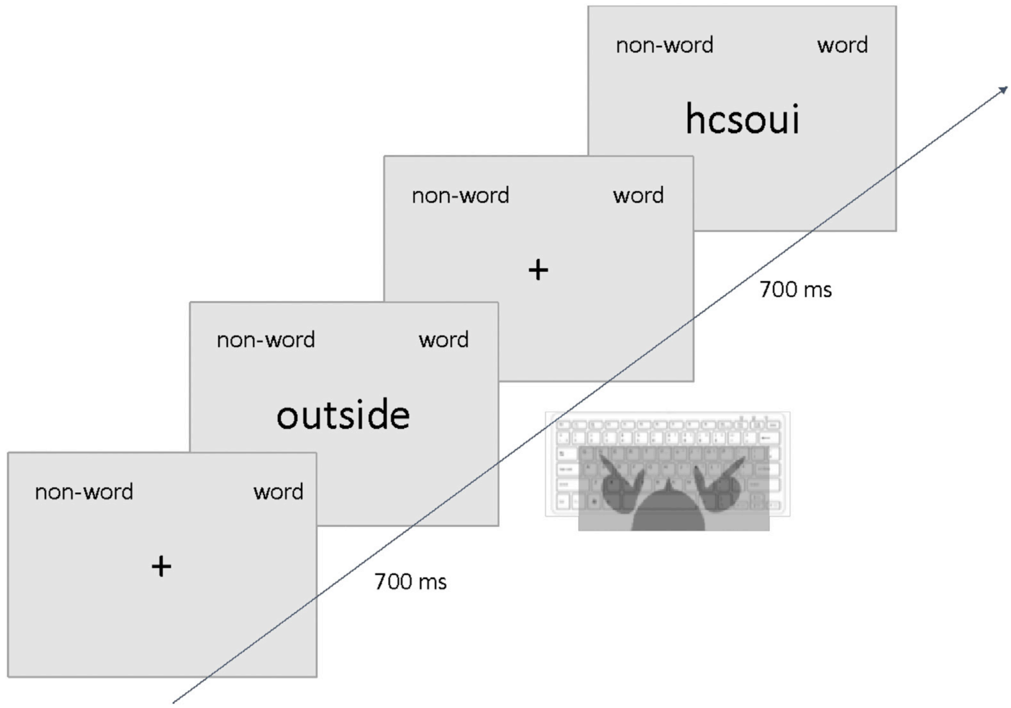

Figure 2. Lexical decision task procedure

Illustration of the experimental procedure used in the LDT.

Next, participants were presented with a series of explicit measures to assess several psychological constructs. First, participants were asked to think about the pieces of information included in the scenario and assess their *relevance*. Then participants were presented with a list of information: the list comprised items on the heat wave (‘‘exceptional heat wave’’), risk of flood (‘‘snow melting’’; ‘‘possible river flooding’’), and risk of fire (‘‘dried vegetation’’; ‘‘possible wildfires spread’’). For each item, participants were asked to indicate the degree of importance of each clue in directing their potential decisions and behaviors in that situation. Then, the overall perceived hazardousness of the scenario was assessed (i.e., ‘‘Thinking about the situation described, how hazardous do you think the scenario is overall?’’). After that, participants were asked to assess the probability of the natural disastrous event given a particular configuration of antecedents (labeling heat wave as H, snow melting as S, and aridity of vegetation as V, the possible combinations are: H S V; ¬H ¬S ¬V; H ¬S ¬V; ¬H S ¬V; ¬H ¬S V; H S ¬V; H ¬S V; and ¬H S V, where the symbol ¬ indicates the nonoccurrence of the event). In the following section, the survey measured risk perception (e.g., ‘‘how likely is this event to occur’’; ‘‘how likely is this event to cause damage to the health of the population?’’) of flooding, wildfire, and compound event (flood & wildfire simultaneously). We emphasize that to avoid conceptual overlap, we differentiated natural hazard perception (intended as the subjective probability of a negative outcome to occur given threatening antecedents) from the outcomes risk perception (that includes the probability of the second-level disastrous events to occur, their probability of causing damages, and their impact on the population in terms of damages). Finally, behavioral intentions were assessed through an explicit scale. Indeed, participants were presented with six statements (e.g., ‘‘In the given scenario, I would be inclined to evacuate’’; ‘‘Under these conditions, it is reasonable for people to stay at home’’) and asked to express their agreement with each statement. Since the internal reliability of the scale was high ($\alpha = .86$), the answers on the items focused on evacuation were reversed, and the composite score averaging the answers on all the 6 items of the scale was computed. Thus, a high level of the scale indicates the inclination to stay at home and a low level suggests a preference for evacuation.

RESULTS

Preliminary analyses on hazard perception

To explore whether participants properly processed the information provided in the scenario, a within-participants eight-level analysis of variance (ANOVA) was computed on hazard perception associated to

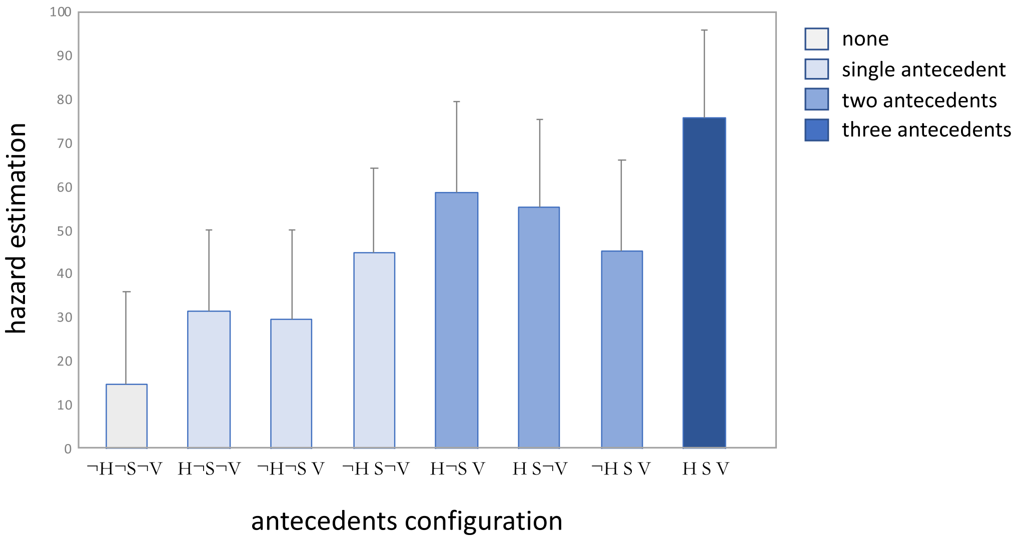

Figure 3. Hazard perception for different configural patterns of antecedents

Level of hazard perception associated with different configural patterns of antecedents. H indicates Heat wave, S, Snow melting, V, aridity of Vegetation; thus the possible combinations are: H S V; ¬H ¬S ¬V; H ¬S ¬V; ¬H S ¬V; ¬H ¬S V; H S ¬V; H ¬S V; and ¬H S V, where the symbol ¬ indicates the nonoccurrence of the event. The plot represents means and SDs for the different configurations.

the configural patterns of antecedents (main hazard and first-level effects; H S V; ¬H ¬S ¬V; H ¬S ¬V; ¬H S ¬V; ¬H ¬S V; H S ¬V; H ¬S V; ¬H S V). The ANOVA yielded a significant effect of configuration, $F(1, 197) = 232.52$, $p < .001$, $\eta^2_p = .54$ (see Figure 3). In line with the scenario goals, as revealed by the post hoc means comparison (LSD post hoc test), the hazard perception in absence of the main cause and the two first level effects (¬H ¬S ¬V) is significantly lower than all the other conditions (all p values < .001). The hazard perception associated with a single antecedent (H ¬S ¬V; ¬H S ¬V; ¬H ¬S V) is significantly lower (all p values < .001) than the case associated with the conjunction of two antecedents (H S ¬V; H ¬S V; ¬H S V) with the exception of the configurations ''melting snow'' (¬H S ¬V) and ''melting snow & dried vegetation'' (¬H S V) that, in absence of the main cause, did not differ from each other ($p = .65$). Moreover, the hazard perception associated with the conjunction of the three antecedents (H S V) is significantly higher than all the other conditions (all p values < .001).

In addition, a multiple linear regression was computed to explore the impact of the different configurations on the overall hazard perception. As displayed in Table 1, the overall hazard perception is significantly predicted only by the conjunction of the main hazard and the two first-level effects (i.e., H S V S).

Then, a within-participants three-level ANOVA was computed on risk perception related to the second-level effects (fire, flooding, and conjunction of fire and flooding). The analysis revealed a significant effect, $F(1, 196) = 95.59$, $p < .001$, $\eta^2_p = .33$. In line with the prior analyses, the perceived risk associated with the combined events ($M = 75.13$, $SD = 14.57$) is significantly higher than the risk associated with single events, flooding ($M = 62.71$, $SD = 15.33$, $p < .001$) and wildfire spread ($M = 64.03$, $SD = 15.39$, $p < .001$). Moreover, confirming that in the scenario the two second-level effects were properly balanced in terms of social perception, the perceived risk of flooding and wildfire spread did not differ from each other ($p = .17$).

Overall, these preliminary analyses suggest that participants properly understood the structure of the risk scenario on compound events and, at a deliberative level, rationally assigned greater risk to the conjunction of antecedents (main cause and first-level effects) and conjunction of negative outcomes (flooding and wildfire spread).

Effects of information subjective relevance on risk perception

Although, at a general level, participants recognized the relation between the events combination and the risk level, the cognitive processing and the relevance assigned to different cues while examining the scenario might vary. Such differences—that in a real setting depend on situational salience (some information

Table 1. Effects of antecedents on hazard perception

Configuration	M (SD)	B (SE)	ß	t-value	p-value
¬H ¬S ¬V	14.60 (21.27)	−0.04 (0.05)	−0.005	−0.07	0.94
H ¬S ¬V	31.57 (18.61)	0.002 (0.06)	−0.08	−1.06	0.29
¬H ¬S V	29.70 (20.55)	0.08 (0.05)	0.06	0.78	0.44
¬H S ¬V	44.80 (19.58)	0.06 (0.06)	0.08	0.88	0.38
H ¬S V	58.64 (20.89)	0.08 (0.05)	0.11	1.51	0.13
H S ¬V	55.15 (20.32)	0.05 (0.06)	0.14	1,69	0.09
¬H S V	45.40 (20.86)	0.009 (0.06)	0.07	0.77	0.44
H S V	75.96 (20.07)	0.29 (0.05)	0.30	3.99	<0.001

Multiple linear regressions of the perceived risk associated to the different configural patterns of antecedents on overall hazard perception.

is likely to be more cognitively accessible than others in a specific context) or individual differences (individual's knowledge, prior experience, and expectations)—are likely to have a critical influence on risk perception and behavioral responses. To investigate some potential effects of information subjective relevance, as a first step, a within-participants three-level ANOVA was carried out (information: heat wave-related; flooding-related; fire-related). The analysis revealed a significant effect, $F(1, 197) = 10.29$, $p = .002$, $\eta^2_p = .05$. The subjective relevance assigned to heat wave-related information ($M = 5.44$, $SD = 1.40$) is significantly lower than importance attributed to both flooding-related ($M = 5.86$, $SD = 1.03$, $p < .001$) and fire-related cues ($M = 5.68$, $SD = .96$, $p = .01$).

Furthermore, a multiple linear regression computed to explore the impact of information relevance on the overall hazard perception revealed that, whereas the heat wave-related cue is not a significant predictor ($B = .03$, $SE = .04$, $ß = .05$, $t = .69$, $p = .49$), relevance assigned to both flooding-related ($B = .23$, $SE = .05$, $ß = .31$, $t = 4.62$, $p < .001$) and fire-related information ($B = .25$, $SE = .06$, $ß = .31$, $t = 4.30$, $p < .001$) significantly increases hazard perception. An analogous pattern of results arose from a multiple linear regression computed to explore the impact of information relevance on the perceived risk of combined events (flooding and fire spread): in line with the previous result, the heat wave-related cue proves to be a nonsignificant predictor ($B = .77$, $SE = .80$, $ß = .07$, $t = .96$, $p = .34$), whereas relevance assigned to both flooding-related ($B = 2.13$, $SE = 1.06$, $ß = .15$, $t = 2.01$, $p < .046$) and fire-related information ($B = 3.20$, $SE = 1.25$, $ß = .21$, $t = 2.57$, $p = .01$) significantly increases risk perception in case of connected extreme events. This pattern of results suggests that perceived risk fostered by the general scenario and the individuals' risk perception associated to the connected extreme events (flooding and fire spread in conjunction) are tailored by the relevance assigned to effect-related cues rather than the antecedent common cause (i.e., the heat wave in our case). Thus, the salience of the cause—that might be perceived as more distal from the negative outcomes, less specific than the first- and second-order effects, and unlikely *per se* to produce the extreme negative events—seems to have a marginal role in the process.

By zooming on the role of the critical cues, i.e., fire-related and flood-related information, we tested the relation between the subjective relevance assigned by participants to these different items and the perceived risk of flooding vs. fire spread. To this aim, we computed a model of moderation using MEMORE, a macro for estimating mediation and moderation in a repeated measures design.[34] To investigate if the relevance assigned to fire-related and flood-related information affects the difference in risk perception associated with flooding vs. fire, we included the two types of risk as dependent variables and the type of information as moderators (Model 2 of MEMORE macro; see Figure 4). The variables have been centered before model computation so that the variables' new mean was zero. As shown in Figure 5, the model revealed a similar significant effect of both fire-related, $B = -2.96$, $SE = 1.08$, $t = -2.75$, $p = .007$, 95% confidence interval (CI) [−5.09, −.83], and flood-related information, $B = 2.73$, $SE = 1.00$, $t = -2.73$, $p = .007$, 95% CI [.76, 4.70], but in the opposite direction. On one side, individuals who assigned greater relevance to flood-related information were prone to perceive higher flood risk, $B = 4.30$, $SE = 1.10$, $t = 3.93$, $p < .001$, 95% CI [2.14, 6.46], but not higher fire risk, $B = 2.23$, $SE = 1.18$, $t = 1.89$, $p = .06$, 95% CI [−.09, 4.57]. On the other side, individuals who assigned greater relevance to fire-related information were prone to perceive higher fire risk, $B = 5.20$, $SE = 1.18$, $t = 4.40$, $p < .001$, 95% CI [2.87, 7.53], but not higher flood risk, $B = 1.57$, $SE = 1.09$, $t = 1.44$, $p = .15$, 95% CI [−.59, 3.73].

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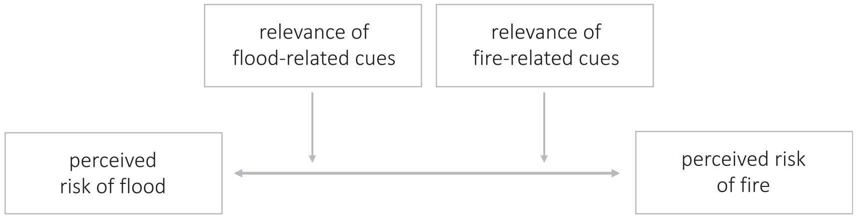

Figure 4. Conceptual schema of the moderation model

The model explores how the subjective relevance assigned to fire-related cues and flood-related ones alters the balance between perceived risk of flood and perceived risk of fire (i.e., risk perception associated to one event regarding the other).

Effects of information subjective relevance on behavioral intentions

Given that the scenario implied a behavioral dilemma (shelter-in-place in case of flooding vs. evacuation in case of fire), we finally explored the potential effects of information subjective relevance and risk perception on respondents' behavioral intentions.

As a first step, we computed an index of cognitive accessibility of thoughts related to the inside (vs. outside) on the answer RTs recorded during the LDT. In line with the cognitive literature, the RTs on practice trials, nonwords, and errors (words classified as nonwords and nonwords classified as words by participants; total number of errors = 104) were excluded from the analyses. Moreover, we excluded 38 trials that were 2.5 SD above the average (RTs >1212.62 ms). The participants' RTs in the classification of outdoor-related words were subtracted from the RTs in classification of indoor-related words (Index = RT_{Indoor} - $RT_{outdoor}$). Thus, since low RTs indicate high cognitive accessibility, a negative composite index reveals greater cognitive salience of the inside than the outside, whereas a positive index reveals greater cognitive salience of the outside than the inside; 0 suggests similarity.

First, it is noteworthy that the index of cognitive accessibility is not correlated with the explicit measure of behavioral intentions ($r = -.01$, p = .88). In line with a large strand of literature in social cognition,[35] automatic, fast, and cognitive uncontrolled processes are not necessarily associated to deliberative thoughts, attitudes, and intentions. To investigate how the index of cognitive accessibility was affected by the relevance assigned by participants to different cues presented in the scenario, we examined a three-way interaction between the relevance of flood-related information, fire-related information, and heat wave-related information on the index, by using PROCESS macro (model 3, 5000 bootstrap resampling).[36] The analysis yielded a significant interaction effect, B = 4.75, SE = 1.90, t = 2.50, p = .01, 95% CI [1.00, 8.50]. As showed by the conditional effects (see Figure 6), the relevance of flood-related information has a significant impact on the accessibility index, B = −20.66, SE = 9.63, t = −2.15, p = .03, 95% CI [−39.65, −1.66], only when the relevance of fire-related information is low (- 1SD) and, at the same time, the relevance of heat wave-related cue is high (+1SD). As revealed by the effect, in such a condition, the more the flood-related cues are salient the smaller is the index, thus showing a cognitive advantage of the indoor concept over the outdoor. In all the other conditions, the effect is nonsignificant (all p-values > .19).

The same model computed on the explicit measure of behavioral intentions did not yield significant results, B = .02, SE = .04, t = .50, p = .62, 95% CI [−.05, .10]. This measure of intentions is negatively correlated with the perceived risk of fire ($r = -.19$, p = .008) and the perceived risk of the combined events ($r = -.24$, $p < .001$). Because a high level of the scale indicates the inclination to stay at home and a low level suggests a preference for evacuation, these results reveal that the greater the perceived risk of fire (or simultaneous fire and flood), the greater the individual's tendency to leave the house during the adverse event. The measure of intentions is not correlated with the perceived risk of flood ($r = -.05$, p = .52).

Finally, a series of moderation models were computed to explore possible effects of gender, place of residence, and prior experience with risk. No model yielded significant results, thus suggesting that the considered individual variables did not affect the processes.

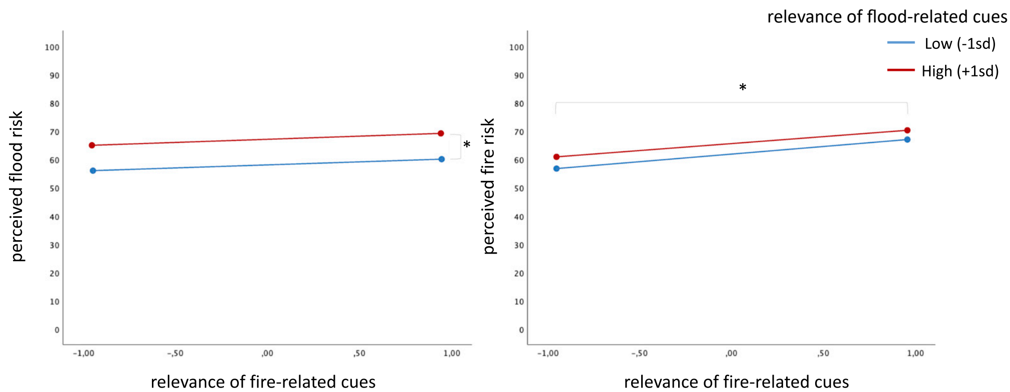

Figure 5. Interaction effect of flood- and fire-related information relevance on risk perception

The plot shows the effect of subjective relevance assigned by participants to flood- and fire-related information on flood and fire risk perception.

DISCUSSION

There is near unanimous scientific consensus that, if drastic actions are not taken, some aspects of climate change will be amplified in the next few years, posing a serious threat to human and natural systems (Intergovernmental Panel on Climate Change, IPCC).[37] Among the environmental menaces, extreme climate-related events and simultaneous occurrence of hazards will become more and more frequent. Thus, environmental sciences and engineering are called to assess and analyze compound events to advance the understanding of the phenomenon. In such a complex scenario, the insights from the "hard" and the "social" sciences should be fruitfully integrated to mitigate the detrimental consequences of compound climate-related events. Indeed, risk perception of private households and local communities is central to understand and anticipate inhabitants' behavior and natural hazard preparedness, with important backlash effects on the actual risk.[38] For instance, underestimating an adverse event can lead people to dismiss mitigation and prevention measures and increase exposure, thus amplifying the potential impact of a natural disaster.

In this perspective, based on prior research in the field of cognitive psychology, this pioneering study aimed to explore the effect on risk perception of the subjective relevance attributed by individuals to hazard- and effect-related cues in a compound events scenario. Moreover, the research investigated the consequences on the individual's behavioral intentions. Overall, the findings revealed that our participants properly recognized that the hazard derived from the conjunction of multiple antecedents (for instance, heat wave and snow melting in our scenario) is significantly greater than the hazard related to a single antecedent (for instance, heat wave in our scenario). Although individuals seem to process information accurately at this first stage of the reasoning, risk perception associated with the outcomes and their impact in terms of damages proved to be affected by the subjective validity assigned to single evidence. More specifically, our data showed that the perceived relevance of flood- or fire-related cues is likely to alter the balance between the perceived risk of flooding and the perceived risk of fire: whereas the relevance level of flood-related cues affects the perception of flooding risk, relevance level of fire-related cues significantly impacts the perception of fire risk. In other words, the specific category of data on which people focus their attention during the information processing is likely to forge different profiles of risk perception. This phenomenon might be particularly pernicious given the individuals' tendency to use single information rather than data configuration during inductive reasoning.[28] Moreover, in a real setting, during an extreme event, the decision-makers might be bounded in time, knowledge, and computational capacity during their analysis, thus being even more prone to such distortions and biases.[39]

A second remarkable result concerns the effects on people's behavioral intentions. Although our data are not clear-cut, it is worthy of note that the configuration of subjective relevance assigned to the different cues provided in the scenario is likely to increase the cognitive accessibility of a specific action (e.g., staying at home) if compared to the opposite one (e.g., evacuating). Furthermore, perception of a specific risk is related to explicit behavioral intentions. In this pattern of results, the inconsistency between the results

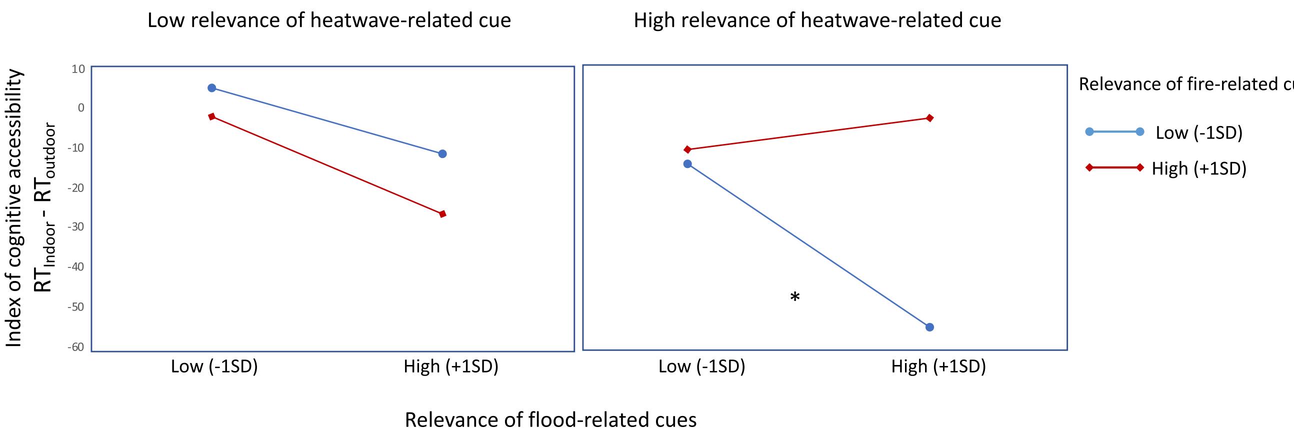

Figure 6. Interaction effect of cues subjective relevance on cognitive accessibility

Interaction effect of the subjective relevance of flood-, fire- and heat wave-related cues on the index of cognitive accessibility (note that a negative index indicates indoor thoughts facilitation over outdoor thoughts).

on explicit and implicit measures of behavioral intentions merits attention. In one case, the cognitive accessibility of action-related thoughts was assessed through implicit methods based on response RTs (LSD task) and, in the other case, participants were overtly asked about their purposes. This apparent incongruity is perfectly in line with several studies showing a dissociation between implicit and explicit attitudes and their coexistence in our cognitive life.[40,41] Indeed, whereas implicit attitudes can be activated automatically and drive our spontaneous behavior outside our conscious awareness,[42] on the other hand, explicit attitudes and intentions guide deliberative and controlled aspects of our decision-making.[43] In some cases, implicit and explicit attitudes lead the behavioral responses toward the same goal; in some other cases, they go in the opposite directions, thus resulting in a low or null correlation between the two types of content. Although prior literature on individuals' risk perception and preparedness mainly focused on explicit behavioral intentions, exploring the role played by implicit attitudes and uncontrolled aspects of decision-making in risk scenarios is critical. Indeed, facing an extreme event, people need to decide how to behave quickly and in the absence of comprehensive information or previous behavioral script. In condition of time pressure, cognitive overload, and anxiety, the impulsive system based on associative network is likely to dominate the behavioral schemata over the reflective system, characterized by explicit decision-making processes.[44]

Furthermore, investigating cognitive processes that underlie behavioral intentions in facing compound events and complex scenarios has important implications. In the study, for theoretical and methodological reasons, we took the situation to extremes by presenting participants with a behavioral dilemma.[45] In such a situation, in the complex causal chains, the greater subjective relevance of specific cues and the related negative outcome over the other might lead individuals to two opposite behavioral answers. If these behavioral intentions translate into actual behavior in a real context, the psychological dominance of one event over the other within the compound is likely to have severe consequences. Going back to our case, if during a compound event the perceived flooding risk prevails, local inhabitants might be prone to adopt the behavior they deem most appropriate to face flooding. However, such conduct is likely to enhance people's exposure to a second hazard (wildfire in our scenario).

Thus, considering psychological processes that intervene in risk perception during compound climate-related events is particularly relevant to improve risk management and communication. Although this first attempt to investigate individuals' risk perception when facing compound events is still at a preliminary explorative stage, the present research aims to highlight the importance of integrating a sociopsychological perspective in risk analysis of climate-related compound events, suggest a methodological approach, and pave the way for future studies. A deep analysis of citizens' psychological processes leading their responses during emergencies is likely to provide relevant insights into how to develop appropriate risk communication strategies. Indeed, in managing crises, public policy and public communication agencies might integrate psychological intuitions to increase public compliance with recommended emergency measures and reduce self-defeating behavior.

Limitations of the study

The study presented here has some limitations that open an intriguing avenue for future research. First, as stated above, investigating comprehensively the psychological processes driving human information processing and behavior during compound events is useful to improve risk estimation and management. However, it is indisputable that assessing the actual impact of such behaviors would require an analysis of the complex patterns of interactions at a population level. To this aim, a helpful tool is represented by the agent-based models (ABMs) that are computational simulations in which a varying number of artificial agents interact over time within environments.[46] As suggested by Aerts,[47] based on empirical data drawn from cognitive and social sciences, the new generation of computational models are called to simulate and investigate how individuals' and communities' behavior affect environmental risk and vice versa.[48] Thus, without integrating the parameters drawn from the psychological experiments into models, it is not possible to evaluate the impact of human decision-making at a large scale.

Second, the scenario devised in our study is specific, thus limiting generalizability of results. As detailed in the introduction section, the class of compound climate-related events is heterogeneous and includes distinct typologies (e.g., interacting, cascading, multi-risk natural hazards[8,49]). Moreover, even considering a distinctive class of compounds, the environmental hazards might be different from those considered in this research. In addition, other typologies of compound events, involving also non-climate drivers could be investigated.[50] Thus, future studies are required to extend these results and test their robustness across scenarios and typologies of compound events. Importantly, not all compound events imply a behavioral dilemma: in most cases, the appropriate behavioral responses to the multiple outcomes are not antagonistic. Indeed, further research is needed to explore cognitive and behavioral responses in case of "synergistic" risks.[51,52]

Furthermore, additional studies should explore not only behavioral intentions but also actual behavioral responses. Indeed, the focus on behavioral intention is an important constraint to ecological validity of this study. In this direction, the virtual and augmented reality (VR/AR) technique would allow to carry out experiments in an immersive virtual reality environment, thus being a useful instrument and exploring human reactions in an experimentally controlled setting. However, even recent studies that used VR to simulate a natural disaster (flooding) assessed the effects on behaviors using explicit measure of behavioral intentions or games.[53,54] On the other side, nonexperimental studies on actual evacuation during natural disasters mainly focus on the characteristics of those who evacuate and those who do not.[55] Moreover, these prior studies explored behavioral reaction in case of single hazard, disregarding compound events. Therefore, a controlled investigation of people's actual behavior in case of compound climate-related hazards is a critical challenge for the future of this line of research.

Finally, assessing risk perception and cognitive processes can only be a partial basis for understanding human decision-making. Many other variables are likely to intervene in a real situation, such as emotions, motivations, perception of personal control, prior experience with environmental hazard, social norms, and communication from institutional agents. A more accurate analysis of the interplay of these different factors is required to predict human behavior and devise appropriate intervention strategies.

ETHICS DECLARATION

The study involving human subjects was in accordance with guidelines of the Declaration of Helsinki.

The protocol was approved by the Ethical Committee of the Department of Psychology, University of Milano-Bicocca (protocol # RM-2022-508). Written informed consent was provided by all participants choosing one of options in the online form.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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AUTHOR CONTRIBUTIONS

C.D.M. and S.S. developed the research idea and aims. All the authors contributed to define the material and procedure. G.F. and S.S. carried out the study and performed the analyses. C.D.M. supervised the research activity. All authors contributed to the interpretation of the results. S.S. drafted the first version of the manuscript, and all authors provided critical revisions. All authors approved the final version of the manuscript for submission.

DECLARATION OF INTERESTS

The authors declare no conflict of interests.

INCLUSION AND DIVERSITY

The authors worked to ensure gender balance in the selection of human participants.

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STAR★METHODS

KEY RESOURCES TABLE

RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Analyzed data	This paper	
Row data and statistical analyses		https://osf.io/9zkwg/
Software and algorithms		
Inquisit web v 6.0	Millisecond Software	https://www.millisecond.com/
SPSS v 27.0.1.0	IBM software	https://www.ibm.com/it-it/analytics/spss-statistics-software
PROCESS	Hayes (2017)	https://www.processmacro.org/index.html
MEMORE	Montoya, A. K., & Hayes, A. F. (2017)	https://www.akmontoya.com/spss-and-sas-macros

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to the lead contact, Simona Sacchi, Department of Psychology, University of Milano-Bicocca, P.zza Ateneo Nuovo 1, 20126 Milan, Italy. Email: simona.sacchi@unimib.it.

Materials availability

Material: The material included in the study is publicly available at https://osf.io/9zkwg/

Data and code availabilitydata-availability

- Data: The dataset generated during this study is available at https://osf.io/9zkwg/
- Code: The statistical codes used for data analyses are available at https://osf.io/9zkwg/
- Any additional information required to reproduce the study and reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Participants were recruited through the platform Prolific (https://www.prolific.co). The sample comprised a total of 198 participants resident in Italy (99 women; 96 men; 2 non-binary and 1 person who did not declare their gender). The age ranged from 18 to 61 ($M = 28.15$, $SD = 8.54$). Thirty-four participants live in a hydrogeological risk prone area; 137 participants in a low risk or safe area (27 participants did not answer this question). One-hundred twenty-seven participants were never affected by a natural negative event; 71 participants witnessed or were personally affected by a natural negative event. No participant was excluded from the subsequent analyses.

The study adopted a correlational method and no factors were experimentally manipulated.

METHOD DETAILS

Participants were invited to take part in the study via Prolific and, through the platform, provided with the link to the InquisitWeb online survey (https://www.millisecond.com). After completing the informed consent, participants were asked socio-demographic questions (gender, age, residence). At the end of the survey, participants were paid around 2.00€ through Prolific, proportionally to the questionnaire duration.

Hazard scenario

In the first part of the study, all participants were presented with a fictitious scenario describing an extreme compound event and asked to put themselves in that situation. The scenario was inspired by the Philip and colleagues's description of a compound extreme event.[30] More specifically, the scenario described a case of extreme heatwave (i.e., hazard) at the end of June in a mountain region. The heatwave dried the vegetation and the soil (i.e., first level effect), thus causing diffused wildfires in the area (i.e., second-level effect and a cascading hazard). At the same time, the heatwave accelerated snow reserves melting (i.e., first level effect) and lead to a critical increase of the river water level (i.e., second-level effect and a cascading hazard). Because of the critical situation the Civil Protection Department raised alert over flood and fire risk. Moreover, the scenario specified that, given the participant's fictitious house position, in case of fire, the individual must evacuate whereas, in case of flood, the individual must adopt a shelter-in-place strategy.

Explicit measures

After reading the scenario, participants were asked to fill out a questionnaire assessing: information relevance; overall risk estimation; the relation between different configurations of antecedents and risk perception; flood, wildfire and compounds risk perception; explicit behavioral intentions.

Information relevance - participants were asked to think about the pieces of information included in the scenario and assess their relevance. Then participants were presented with a list of information: the list comprised one item on the "exceptional heatwave" (cause); two items related to risk of flood ("snow melting"; "possible river flooding"; $r = .50$, $p < .001$); two items related to risk of fire ("dried vegetation"; "possible wildfires spread"; $r = .28$, $p = .007$); and some fillers (irrelevant items; e.g., "the season"). Participants were asked to indicate the degree of importance of each clue in directing their potential decisions and behaviors in that situation on a 7-point scale ranging from 1 (totally irrelevant) to 7 (totally relevant).

Overall hazard perception - next, participants were asked to estimate the overall hazardousness of the scenario (i.e., "Thinking about the situation described, how hazardous do you think the scenario is overall?") on a 7-point scale ranging from 1 (not at all) to 7 (very much).

Configurations of antecedents - in the subsequent section of the questionnaire, participants were asked to assess the probability of the natural disastrous event given a particular configuration of antecedents: Heatwave (H; i.e., the cause); dried Vegetation (V; i.e., first level effect); Snow melting (S; i.e., first level effect). Thus respondents were presented with a list of 8 combinations: H S V; ¬H ¬S ¬V; H ¬S ¬V; ¬H S ¬V; ¬H ¬S V; H S ¬V; H ¬S V; ¬H S V (where ¬ represents here the non-occurrence of the event). The answers were provided on a 11-point scale ranging from 0% to 100%.

Outcomes risk perception - then an assessment of risk perception was displayed. Participants were asked to assess the risk perception of the negative event on three items: probability of the event occurrence (e.g., "In this situation, how likely is the river to overflow AND a wildfire to break out at the same time?"); probability of damages for the population in case of event occurrence (e.g., "In the case only a wildfire breaks out, how likely is this event to cause damage to the health of the population?"); damage severity in case of event occurrence (e.g. "If only the river overflows and this event causes damage to the health of the population, how severe do you think this damage would be?"). The answers were provided on a 11-point scale ranging from 0% to 100%. The three items of risk perception were presented three times associated to the two single negative events (i.e., flood only, $\alpha = .62$; wildfire only, $\alpha = .63$) and their conjunction (i.e., flood & wildfire, $\alpha = .61$).

Explicit behavioral intentions - finally a 6-item scale of behavioral intentions ($\alpha = .86$) was presented to investigate participants' preferences for evacuation vs. shelter-in-place strategy . Three items were focused on evacuation (e.g., "In the given scenario, I would be inclined to evacuate"), the other three items on staying at home (e.g., "Under these conditions, it is reasonable for people to stay at home"). Participants were asked to express their agreement with each statement on a scale ranging from 1 (not at all) to 7 (very much).

Implicit measures

The present LDT explored the facilitation of thoughts related to the two opposite behavioral alternatives (staying at home vs. evacuating). In the first screen, instructions were provided: as in a typical LDT, participants were informed they would be presented with words and nonwords and asked to determine as quickly as possible whether a letter string was or was not a word. Each trial began with the presentation of a cross at the center of the screen (fixation point); after 700 ms, a stimulus was presented at the center of the screen. At the beginning, six practice trials unrelated to the present topic were administered. In the study, two groups of lexical stimuli were presented (the original words were in Italian): the first group included 8 words related to the outside (outdoor, street, open, outside, field, exit, go, broad), the second group comprised 8 words related to the inside (indoor, home, close, inside, room, enter, stay, confined). Moreover, the words used in the study were scrambled to create non-words (16 trials) of equal length. Participants were required to categorize each stimulus appearing on the screen by pressing on the keyboard the key "E" whether it was a non-word or "I" whether it was a word. The 32 trials were displayed randomly. Participants' reaction time (RTs) were recorded. Faster RTs in a stimulus categorization indicate higher cognitive accessibility: indeed, prior cognitive research on lexical decision experiments revealed that the amount of time to decide that a letter string is a word is shorter when the related concept is cognitively salient.

QUANTIFICATION AND STATISTICAL ANALYSIS

All the statistical analyses and the results are described in the main text (See results section). Data are displayed in Table 1 and in Figures 1, 2, 3, 4, 5, and 6.