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Understanding microworlds

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Little is known about how individuals understand change in complex systems. In the natural world, for instance, the effects of change need to be understood in terms of two-way (interdependent) causal processes. Based on subject's ratings of the causal likelihood that a given change will yield a target effect and on subjects' ratings of the impact of a given change on specified populations in a microworld, White (1997, 2000) argued that individuals in fact understand change in terms of one-way causal processes and assume that causal effects decline with distance from the source of the change. An alternative view is that the ratings reflect individuals' mental simulations of change as elicited by the tasks. Experiments 1 and 2 confirm that such ratings are task dependent and that individuals make no general assumption that causal effects decrease with distance. Experiment 3 shows that when required to explain a pattern of change in the size of a population individuals can construct two-way causal explanations consistent with this mental simulation proposal.

INTRODUCTION

Fundamental to many human systems (e.g., the economy) and to natural systems or foodwebs are interdependent chains of cause and effect. Yet we known little about how individuals understand such systems or what constrains their understanding. This is surprising given the importance of the issue to practical concerns such as environmental policy. Consider a population of rabbits and foxes. An increase in the number of rabbits can lead to an increase in the number of foxes (a positive feedback loop), which will lead to a decrease in the number of rabbits (a negative feedback loop). Causal relations are two-way and involve both positive and negative feedback loops. Do individuals grasp such two-way causality? There is disagreement. We first outline the disagreement and then propose a solution. The studies described focus on the understanding of microworlds—artificial foodwebs that comprise plants, herbivores, and carnivores.

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White (1995, 1997) proposed on the basis of empirical data that naïve individuals assume that causal influence propagates through a foodweb/microworld in one direction only and also that causal influence diminishes with distance from the source of the change. So, for instance, climate change affects the number of plants, and the number of plants affects the number of herbivores, but climate change has less of an effect on herbivores than on plants. Recently, White (2000) has conjectured, more specifically, that individuals think of foodwebs in terms of a basic physical model—the force-resistance model (diSessa, 1983, 1993). Foodwebs are characterized by the passage of energy (Ricklefs, 1993), and it is reasonable that judgements about change in an artificial foodweb will be affected by naïve views of this energy transfer function. White (e.g., 1997, 2000) has used two different judgement tasks that show a comparable and robust effect.

In the causal likelihood judgement task (White, 1997) individuals judge the causal likelihood that different control actions (e.g., changing the amount of a plant, altering the population of a given herbivore) will achieve a target effect (e.g., increasing the population of a specific carnivore). Rated causal likelihood decreases as a function of distance in links (roughly, the number of intervening populations) between the point of the control action and the target effect. In the impact judgement task (e.g., White, 1997, 2000) individuals judge the impact of some change (e.g., a change of climate) on each of the populations in a microworld once the populations have become stable again—that is, naturally maintain themselves at the same level bar outside interference. Rated impact also decreases as a function of the distance in links from the point of perturbation. In both cases, for the sake of convenience, we will say that there is a distance effect rather than a "dissipation effect" (the term used by White, 1997, 2000) as this term conflates a description of the observed effect with its interpretation.

Distance effects are consistent with one-way causal thinking and, more specifically, with the notion that a perturbation (e.g., global warming) provides a force that travels through channels of the foodweb and encounters resisting entities. The amount of judged change at some point (for instance, on the number of carnivores that predate on herbivores that eat a plant that prefers warmer conditions) is the result of a contest between the perturbing force and resistance to it with the effects of the force tending to dissipate with each successive encounter. Such a conception may also mediate judgements of causal likelihood. We term this conjecture the dissipation hypothesis—it is a hypothesis that combines the idea of one-way causal influence with the idea of diminishing causal effects.

In contrast to these results, Green (1997, Experiment 4) found that individuals can explain a pattern of population change, or envisage how populations might change following a perturbation, in terms of two-way causal processes, at least when only two population (trophic) levels are involved. In doing so, they make use of what they know about plant and animal populations and how they affect one another. The problem for the dissipation hypothesis is that if individuals invariably engage in one-way causal thinking (perhaps because they apply force-resistance concepts to the problem), it is unclear how two-way causal accounts can arise at all. In the next section, we consider an alternative proposal that can explain both the distance effects reported by White (1997) and the data described in Green (1997, Experiment 4).

Mental simulation

The dissipation hypothesis presumes that individuals represent the microworld abstractly and apply a physical principle (e.g., diminishing causal effects) to generate task responses. An alternative possibility is that individuals construct specific mental representations or mental models (Craik, 1943; Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991) of the microworld. In doing so, they make use of the description of the microworld and what they know about plant and animal populations and how they affect one another. Tokens in the model and relations between tokens correspond to the entities and their relations in the world. The basic proposal is that in order to assess the effect of a control action, or the impact of a given population change, individuals run their mental model—that is, they mentally simulate the change (Kahneman & Tversky, 1982). Ratings reflect the outcome of these simulations in the context of the task.

A basic supposition of the theory of mental models is that individuals minimize what they represent explicitly (Johnson-Laird & Byrne, 1991) and so not all possible relations amongst the entities will be encoded explicitly in their initial mental model. In this sense the theory is consistent with a basic supposition of the rational analysis of human behaviour (e.g., Anderson, 1991; Simon, 1978) that individuals seek to optimize, doing no more than that required to achieve a particular expected benefit or to achieve a relevant response (see Sperber & Wilson, 1986, for a comparable notion in the context of human communication). Simple solutions will be preferred to more complex solutions (see Chater, 1999, for a recent exposition on simplicity as a guiding principle in human cognition, also Chater, 1997).

The subject's task will affect the nature of the mental simulations and, in particular, the extent to which the initial model of the microworld is fleshed out with other relations expressing an interdependency amongst the populations. Responses may accordingly provide evidence of one-way causal thinking with diminishing causal effects in the case of some tasks (e.g., the version of causal likelihood task used by White, 1997) but two-way causal thinking in other tasks, such as one demanding the causal explanation of a pattern of data, which may elicit more extensive mental simulation.

Consider the causal likelihood task (White, 1997) and the microworld depicted in Figure 1. Mental simulation will show that an increase in the number of herbivores (H1) will increase the number of carnivores (C1). Mental simulation will establish too that an increase in the number of plants (P1) can yield an increase in the number of carnivores (C1) via an increase in the number of herbivores (H1). The presence of alternative possible causes (i.e., successful simulation of the effect using various populations) questions the *necessity* of the current cause to the effect. Causal likelihood judgements may then be most sensitive to factors that lower the probability that the effect will occur given the current cause. They will be most sensitive, that is, to disabling conditions (Cummins, 1995; Cummins, Lubart, Alksnis, & Rist, 1991; Fairley, Manketelow, & Over, 1999). Such conditions can prevent the effect from occurring and so undermine the *sufficiency* of the causal factor. The causal likelihood task used by White requires individuals to consider the causal potential of each population. There is a pragmatic presumption in this task, and in the impact judgement task, that relevant judgements should

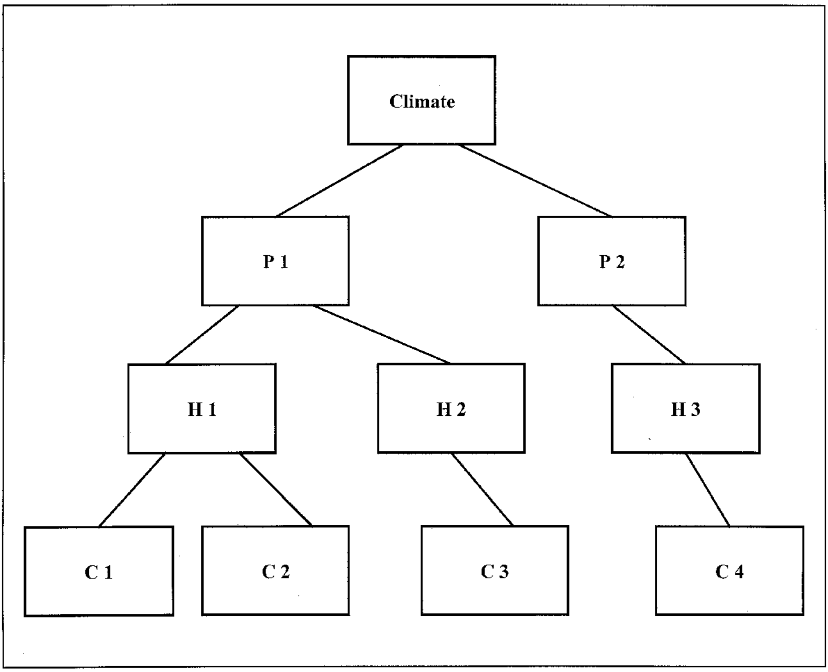

Figure 1. Depiction of the microworld used in Experiments 1 and 2.

differ from one another (cf., Sperber & Wilson, 1986). In consequence, when they mentally simulate the causal effect of a change in climate, for instance, and generate judgements based on their mental simulations, individuals may reason that compared to a change in plant P1, they have fewer reasons to doubt that a change in the population of herbivores H1 will alter the population of carnivores C1, as a change in P1 also requires that H1 changes in the expected way. They will accordingly give a higher rating of causal likelihood to H1 than to P1.

This line of argument relates directly to research on conditional inference. In reaching a judgement in the causal likelihood task, individuals are effectively judging the certainty of a conclusion (e.g., "C1 changes by a certain amount") to a conditional statement (i.e., "If the climate changes then C1 changes by a certain amount") given the antecedent of the conditional (i.e., the control action that "the climate changes").

Developing the critical proposal and technique of Byrne (1989), Stevenson and Over (1995) showed that alternative conditions for the achievement of a conclusion increased the judged uncertainty of a conclusion (see also George, 1995, Experiment 3 for a related observation). Most relevant here is the work of Cummins (1995; Cummins et al., 1991) on causal conditionals. She showed that the acceptance rating of a conclusion decreased with the number of disabling conditions (for related studies, see also Thompson, 1994, 1995). In White's (1997) version of the causal likelihood task, individuals assess the certainty of the conclusion in the context of other antecedents ("If the number of plants changes"; "If the number of herbivores changes"). Such a task makes evident possible disabling conditions.

On the present proposal then the distance effect requires no special explanation. It is predictable given the mental simulations required by the task. It follows that the distance effect is likely to be a task-dependent effect. Experiment 1 examines this conjecture by determining whether or not a distance effect occurs when individuals are required to make just a single judgement. In such a task, the alternative conditions (possible populations to control) are not mentioned explicitly, and so, according to the mental simulation proposal, there is no reason for individuals to simulate their effects mentally, and there will be no distance effect. That is, the proportion of individuals judging a population as the one to control will not vary inversely with its distance from the target effect (see Experiment 1 for details).

Consider next the impact judgement task that assesses individuals' views on how the size of the various populations changes under a perturbation such as a climate change. On the mental simulation proposal, individuals use their knowledge of relative population sizes and represent in their mental model more tokens of plants than tokens of herbivores and represent more tokens of herbivores than tokens of carnivores. Suppose individuals mentally simulate a change in climate by taking some constant proportion (e.g., 10%) of each of the population tokens. If individuals then base their impact judgements on the *number* of tokens corresponding to plants, herbivores, and carnivores affected by their mental simulation (or on the number of tokens corresponding to these populations in their post-simulation model) then there will be a distance effect simply because the number of plants affected will be greater than the number of herbivores affected, which in turn will be greater than the number of carnivores affected.

Experiment 2 assesses this mental simulation proposal by examining whether or not the distance effect also occurs when individuals are asked to estimate the original and final numbers of a population. In such a case, different numbers can be produced for each population level, but if individuals generate such numbers by taking a constant proportion of the original figure, the computed percentage change across different populations will be constant, and there will be no distance effect, contrary to the dissipation hypothesis.

Experiments 1 and 2 establish that judgements are task dependent and so refute the claim that individuals envisage that causal effects dissipate with distance. However, neither establishes that individuals can think about change in terms of two-way causal processes. Experiment 3 adopts a different tactic in order to address this question. It asks individuals to explain a pattern of change to a herbivore population given a rise in temperature. In this case, according to the mental simulation proposal, individuals construct an initial mental model and attempt to simulate the pattern of change. If it does not fit, then individuals can adapt or change their initial model (cf., Clement, 1993). To the extent that they judge that the simulation yields a good fit, then a written-down version of the history of the simulation provides an abductive explanation of the pattern in Peirce's terms (Feibleman, 1960).

On this proposal, individuals seek a causal process sufficient to generate the pattern of data. There is no claim that individuals establish whether or not the pattern of data could have occurred via some other causal sequence. The mental simulation proposal, in other words, makes no claim that individuals engage in counter-factual thinking in order to reach an abductive explanation.

A number of researchers (e.g., Hilton, 1990; Kahneman & Miller, 1986; Lewis, 1973; Mackie, 1974) have assumed an intimate connection between counter-factual thinking and causal thinking. Individuals on this view reach a causal judgement by determining whether or not the effect could have occurred in the absence of the putative cause. However, experimental data show that individuals focus on different events when asked to undo mentally an outcome compared to when they are asked what caused an outcome (e.g., Mandel & Lehman, 1998; N'gbala & Branscombe, 1995). Individuals tend to undo events that were necessary for an outcome when they think counter-factually whereas in the case of causal explanations they focus on antecedents that are sufficient to produce an outcome (N'gbala & Branscombe, 1995). Indeed, McEleney and Byrne (2000) argue on the basis of convincing empirical data that the functions of counterfactual and casual thinking are different: The former seeks to identify actions that could prevent an outcome from occurring whereas the latter seeks to identify actions or conditions that predict an outcome.

The artificial foodwebs or microworlds used in the experiments have certain advantages (see White, 1997). They allow one to examine general processes of thinking rather than ones based on very specific knowledge about particular populations. A comparable strategy is used in studies of causal attribution (see Cheng & Novick, 1990) and of other cognitive processes (e.g., the Wason selection task, Wason, 1968). Further, the precise problems cannot have been anticipated either by evolution (pace Cosmides & Tooby, 1994) or by schooling. Indeed in the present studies, there was no effect of whether or nor individuals had taken biology or ecology as academic subjects, and so the data reported are summed over this factor.

EXPERIMENT 1

In order to assess the effect of task on causal likelihood judgements, we used an adapted version of the microworld described in White (1997, Problem 1) and represented in Figure 1. Individuals were required to create a stable 5% change in the population of Carnivore 1. Technically, creating a stable change in animal population requires a change in climate. Climate is an external-forcing function (Ricklefs, 1993) and so, for instance, provides energy for an increase in a plant population and for a stable increase in the animal populations dependent on that plant.

White (1997) required individuals to rate explicitly the effectiveness of different factors in achieving the change in the target population. If individuals generally consider that a causal influence dissipates with distance (perhaps because they apply force-resistance concepts to the problem), as the dissipation hypothesis supposes, then they should also elect to control a factor closest to the target when required to identify a *single* suitable control action (i.e., they should seek to control the size of the herbivore population, H1). In order to check this prediction, the performance of individuals required to identify a single suitable factor (the no rating condition) was contrasted with the performance of individuals in a rating condition who were required to rate the causal efficacy of each factor as in White (1997).

If, on the other hand, the distance effect is task specific, as supposed by the mental simulation proposal, then performance should change in these two conditions. The rating condition requires multiple simulations, and these provide grounds for believing why a particular control action may not achieve the target effect. In contrast, in the no rating condition it is sufficient for individuals to identify a single plausible causal pathway. If they select a population at random and then simulate its causal effects, they will be no more likely to judge that the population closest to the target population is the one to control compared to any other. More plausibly, the causal relation between climate and plants is represented mentally as causally prior to that between herbivores and carnivores. In this case, mental simulation will show that the target effect can be achieved by altering the climate, and so individuals will endorse climate as the factor to control—a factor distant from the target effect.

The mental simulation proposal therefore predicts increased selection of climate (the technically correct answer) in the no rating condition compared to the rating condition, whereas the dissipation hypothesis predicts that individuals in both conditions will identify the herbivore population (H1) as the optimal factor to control.

An alternative line of thinking also suggests a difference between these two conditions and bears mention at this point. Research on counter-factual thinking indicates that when individuals think about how an outcome could have turned out differently they tend to undo the *first* cause in a connected sequence rather than any subsequent ones (e.g., Wells, Taylor, & Turtle, 1987). We might expect then that when asked to identify a single factor to control (in order to change the carnivore population) individuals would identify the climate—the first cause in a connected sequence. The fact that they do not do so when required to rate the causal likelihood of each individual factor might then be taken to mean that this rating task restricts individuals' perceptions of connectedness. Indeed, in the case of a set of independent events, individuals do tend to change the *last* event in a series rather than any earlier one (Miller & Gunnasegaram, 1990). One reason individuals act in this way is that they presuppose earlier events in an independent sequence (see Byrne, Segura, Culhane, Tasso, & Berrocal, 2000). However, there are two problems with this line of thinking. The first problem is that it lacks parsimony: It supposes a radically distinct perception of the microworld in the rating and in the no rating conditions. The second problem is that there is no evidence that individuals spontaneously engage in counterfactual thinking when thinking about the cause of an event (see McEleney & Byrne, 2000).

Method

Participants

Participants were 105 adults (20 male, 85 female) with a modal age of 18 years (range: 17–42 years) attending for interview for a place on the undergraduate psychology programme.

Design and procedure

Individuals were assigned at random to one of two conditions—the rating condition and the no rating condition—and were run in two large groups. The microworld problem was one of a set of problems designed to illustrate ongoing research in the department. Individuals were free to participate or not in the study. It was stressed that neither participation nor performance played a role in the offer of a place. Participation was transparently anonymous, and the purpose of the study was explained after the session.

Materials

The microworld was described exactly as follows:

Plant P1 grows best under warm dry conditions.
Plant P2 grows best under cool wet conditions.
P1 and P2 compete for space: the more space one has, the less the other has.
Animals H1 and H2 eat plant P1 only.

Animals C1 and C2 eat H1 only.
Animal C3 eats H2 only.
Animal H3 eats plant P2 only.
Animal C4 eats H3 only.

Individuals in the no rating condition were instructed as follows:

The following question concerns the cause of a stable change. By stable change is meant a change in which the population in question will naturally maintain itself at that level year after year barring some outside interference. Assuming you could control the microworld what factor would you change to a cause a stable 5% change in the population of C1? You can allow time for any change to take effect but you have no further control after altering the one factor you choose. Why do you think the action you chose will succeed?

In the rating condition, the instructions were as follows:

The following question concerns the cause of a stable change. By stable change is meant a change in which the population in question will naturally maintain itself at that level year after year barring some outside interference. Assuming you could control the microworld what factor would you change to cause a stable 5% change in the population of C1? You can allow time for any change to take effect but you have no further control after altering the one factor you are allowed.

Possible actions are listed below. Please rate each one in terms of its likelihood of achieving the stable change on a scale from 0 to 100 where 0 means that the action has no chance of success and 100 means that it is certain to lead to the required change.

Make the weather warmer
Make the weather drier
Increase plant P1
Decrease plant P2
Increase H1
Decrease H2
Increase H3
Decrease C2
Increase C3
Decrease C4

Why do you think the action you rated highest will succeed?

The order of these various actions was varied over participants. Individuals were asked to create a stable change. In the context of the presented control actions this effectively meant an increase in C1.

Results and discussion

Individuals in the rating condition were asked to give the highest rating to the factor that they considered most likely to achieve the goal. Table 1 displays their mean causal likelihood ratings (out of 100) as a function of causal locus expressed in terms of distance in links from the target of the control operation, C1. So, for example (please see Figure 1), climate is a distance

TABLE 1
Experiment 1: The number and percentages of participants selecting each locus[a] as a function of condition

	Locus of control									
	1		*2*		*3*		*4*		*5*	
Condition	*No.*	*%*	*No.*	*%*	*No.*	*%*	*No.*	*%*	*No.*	*%*
No ratings	3	6	16	31	30	58	1	2	2	4
Ratings[b]	12	23	32	60	8	15	1	2	0	0
	Causal likelihood ratings for each locus[c]									
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Ratings	60.8	33.9	59.4	22.0	46.4	21.4	29.1	26.0	15.6	20.9

[a] Expressed in terms of the number of links/populations separating the control action and the target effect.
[b] Corresponds to the locus with the highest rating.
[c] Out of 100.

of three links from the target (via plant P1 and herbivore H1). P1 is a distance of two links from the target, and H1 is a distance of one link from it (see White, 1995). In line with previous findings by White (1997), rated causal likelihood in this condition declines systematically as a function of distance from the target—there is a distance effect.

A single-factor analysis of variance (ANOVA) of these data with causal locus as a within-subjects factor with five levels confirmed a significant difference over loci, $F(4, 208) = 43.01$, $p < .001$, together with a highly significant linear polynomial, $F(1, 52) = 162.66$, $p < .001$, with no significant residual error, $F = 3.12$, n.s.

Individuals in the no rating condition nominated one factor that they would control to achieve the stable change. Table 1 shows the distribution of their decisions expressed in terms of distance in links from the target of the control operation. Also displayed is the distribution of the control actions with the highest causal likelihood rating in the rating condition. Consistent with the mental simulation proposal, there is a significant effect of task on these distributions: A chi-squared test on these data yielded, $\chi^2(4, N = 105) = 23.43$, $p < .001$. The modal locus of control is two-links distant from the target in the rating condition and three-links distant in the no rating condition. More specifically, 51.9% (27/52) of participants correctly selected climate (three links distant from the target) in the no ratings condition as compared to just 7.5% (7/53) of participants in the rating condition, $\chi^2(1, N = 105) = 16.24$, $p < .001$. Such an outcome is particularly striking given that climate was not presented as a possible factor to control in the no rating condition whereas it was presented as an explicit factor to control in the rating condition.

The task-dependent nature of causal likelihood judgements refutes the dissipation hypothesis but is consistent with the mental simulation proposal. The fact that individuals more frequently select the correct control action (i.e., changing the climate) when they are required to identify a single control action does not entail that this no ratings condition elicits two-way causal thinking. On the contrary, one-way causal thinking is sufficient for the task—individuals need only trace the impact from the origin of the causal path (climate) through an increase in P1 and consequent changes in the dependent animal populations.

EXPERIMENT 2

The judged impact of a perturbation on a population also decreases linearly with distance from the point of the perturbation (White, 1997, 2000). There seems no reason to doubt the reliability of the effect given the number of replications (see White, 2000; see also Footnote 1). However, these replications have all used the same rating task, and so it is conceivable that the result is task dependent as suggested by the mental simulation proposal.

The present study contrasted two conditions in order to explore this possibility: a direct percentage condition and an indirect percentage condition. In both conditions individuals judged the impact of a climate change (a small increase in temperature) on each of the populations in the microworld. As climate is an external forcing function, the technically correct answer is that a small increase in temperature will lead to changes in the size of each population and that the impact of these changes will be constant—that is, there will be no distance effect. In the direct percentage condition, participants registered the percentage change from the original population. In the indirect percentage condition, in contrast, they first estimated the size of each of the populations before any change occurred. They then indicated the amount of the change. The experimenter later computed the percentage change in the population.

If the dissipation hypothesis is correct then judgements will decline with distance in both conditions rather than remain constant, as individuals derive their estimates either on the assumption that causal effects decline with distance or by deploying the force-resistance model that yields the same outcome. If the mental simulation proposal is correct, then individuals in the indirect percentage condition will show no distance effect whereas those in the direct percentage condition may well do so.

On the mental simulation proposal, individuals in both conditions use their knowledge of population relations and mentally envisage that there are more tokens of plants than tokens of herbivores and more tokens of herbivores than tokens of carnivores. In mentally simulating change, we assume that they minimize mental effort and transform each set of tokens by the same proportion. In consequence, in the indirect percentage condition, the computed percentage changes will be constant despite the fact that the sheer number of individuals affected given a change in climate will decline across population levels. In contrast, in the direct percentage condition individuals must additionally, in order to compute this figure, recall the different numbers of tokens representing the original population sizes. In practice, they may fail to do so and base their judgements on the relative number of different population tokens in their current mental model. In consequence, their percentage impact judgements will show a distance effect in line with the impact judgements reported by White (1997, 2000). They may ignore the size of the original population (cf., the tendency to ignore base-rate information, Cascells, Schoenberger, & Graboys, 1978) either because of memory constraints or because judgements based on the number of tokens for different populations generate responses consistent with the pragmatic expectation that different impact judgements are required.

White (2000) has recently reported further evidence consistent with the force-resistance model. We consider one example here. Suppose the two carnivores (C1 and C2) feed exclusively on a single herbivore such as H1 as in Figure 1. White found that the rated impact of change was much less for such carnivores than for a carnivore (C4, say) that is the sole predator of a herbivore, H3. It is as if the effects of the change are dissipated down two different channels in the case of C1 and C2 but not in the case of C4. But suppose that individuals envisage that the population size of C1 and C2 together is roughly equal to that of C4. If they then assess the impact in terms of tokens of the envisaged numbers, they will rate the impact of the change on C1 and C2 as roughly half that of C4. In contrast, for individuals in the indirect percentage condition, the computed percentage change could well be constant even in this case.

Method

Participants

Participants were 50 individuals (17 males, 33 females) attending for interview at the Psychology Department (UCL), model age 18 years (range 17–20 years).

Design and procedure

Individuals were assigned at random to either the direct percentage condition ($N = 25$) or to the indirect percentage condition ($N = 25$). Other aspects of the procedure were as before.

Materials

The microworld was simpler than that used in Experiment 1. The materials for the direct percentage condition read exactly as follows:

Imagine the following microworld:

Plant P1 grows best under warm conditions.
Plant P2 grows best under cool conditions.
P1 and P2 compete for space: the more space one has, the less the other has.
Animal H1 eats plant P1 only.
Animals C1 and C2 eat H1 only.
Animal H3 eats plant P2 only.
Animal C4 eats H3 only.

Imagine now a climate change such that the microworld becomes somewhat warmer (by two degrees C). How might this climate change affect, if at all, each of the populations (plants and animals) such that after the change has become established each of the populations are once again stable? A **stable population** is one that naturally maintain itself year after year at the same size, barring outside interference.

Please indicate your view by expressing it as a percentage and writing one number between 0% and 100%.

If you think there will be "No change" from the original stable population, write 0%. If you think there will be a change, write a plus sign (+) for an "Increase" and a minus sign (−) for a "Decrease". Where you think a change will occur, how large will it be? Please indicate the **change** from the original size—a larger percentage indicates a larger change. Thank you!

Effects of climate change

0%..........100%
P1 ____
H1 ____

C1	____
C2	____
P2	____
H3	____
C4	____

The materials for the indirect percentage condition described the same initial microworld and continued as follows:

Imagine the sizes of the various animal populations such that there is a **stable population** of each. That is, a population that naturally maintain itself year after year at the same size, barring outside interference. Please indicate in the table below, very approximately, the number of each type of animal that might make a stable population **in your view**. P1 covers 100 square miles and P2 covers 100 square miles. Please put your estimates of the numbers of each animal population in the *Original size* column—expressed, according to your view, for the population in question, either in tens (e.g., 50), or in hundreds (e.g., 400), or in thousands (e.g., 2000).

	Original size		*Effects of climate change*	
P1	100	*square miles*	____	*square miles*
H1	____		____	
C1	____		____	
C2	____		____	
P2	100	*square miles*	____	*square miles*
H3	____		____	
C4	____		____	

Imagine now a climate change such that the microworld becomes somewhat warmer (by two degrees C). How might this climate change affect, if at all, each of the populations (plants and animals) such that after the change has become established each of the populations are once again stable—i.e., naturally maintain themselves at that size, year after year, barring outside interference?

If you think there will be no change from the size of the original stable population of the animal or plant in question, put "0" in the column headed *Effects of climate change*. If you think there will be a change, write a plus sign (+) for an "Increase" and a minus sign (−) for a "Decrease". Where you think a change will occur, how large will it be? Please indicate the **change** from the original size, e.g., if you think a plant type might decrease by 20 sq. miles, write −20 sq. miles; if you think an animal population might increase by 500 animals, write +500.

Thank you!

Results and discussion

Table 2 displays the average estimated percentage changes for populations in the microworld as a result of a climate change for each of the conditions. We distinguish two pathways (see Figure 1). Pathway 1 comprises, P1, H1, and C1 and C2 (data for C1 and C2 were averaged).

TABLE 2
Experiment 2: Percentage estimated mean change in population size given a climate change as a function of condition, locus and pathway

		Locus[a]					
		1		*2*		*3*	
Pathway	*Condition*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	Indirect percentage	49.9	46.0	46.7	49.1	57.9	78.9
	Direct percentage	37.2	24.8	30.8	22.6	21.1	16.0
2	Indirect percentage	39.5	24.7	31.7	20.4	35.0	24.7
	Direct percentage	35.2	19.5	37.6	19.5	43.6	21.9

Note: The values for locus 3 in Pathway 1 average the data for C1 and C2 (see text for explanation).
[a] Expressed in terms of the number of links/populations separating climate and the target effect.

Pathway 2 comprises P2, H3, and C4. For each pathway, the plant, herbivore, and carnivore populations are at, respectively, one, two, and three links distance from climate. The pathways were distinguished because sample data[1] with the impact rating task used by White (1997, 2000) showed a reduced distance effect for Pathway 2. In the case of the indirect percentage condition, the percentage change data were computed: The actual change recorded for each population was divided by the original population size supplied by the participant (bar the plant population that was given) and multiplied by 100 to yield the percentage change. In all cases, increases were correctly reported for Pathway 1 and decreases for Pathway 2.

As can be seen, in the indirect percentage condition judged impact did not decline systematically with distance (locus) for either pathway. In contrast, for the direct percentage condition, the outcome is more equivocal. For Pathway 1, impact judgements decrease with distance. In contrast, for Pathway 2, there is a tendency for these judgements to increase with distance—an outcome largely attributable to the impact ratings for C4, which are double those reported for C1/C2 in Pathway 1. In fact, overall judged impact is higher for Pathway 2 than for Pathway 1.

The data were subjected to a mixed factor ANOVA with condition (direct percentage and indirect percentage) as the between-subjects factor and pathway (Pathway 1 and Pathway 2) and locus (plant, herbivore, and carnivore levels) as the within-subjects factors. In line with impressions, there was a two-way interaction between condition and pathway, $F(1, 48) = 7.65$,

[1]A small number of individuals (n = 14) from the same population as the main study gave impact judgements for the same microworld using the method adopted in White (1997, 2000). An ANOVA of these data with the within-subjects factors of locus and pathway showed that there was an overall effect of locus, $F(2, 26) = 8.28$, $p < .005$, such that rated impact decreased from Locus 1 (42.22), through Locus 2 (32.50) and Locus 3 (26.50). There was also a significant interaction between locus and pathway, $F(2, 26) = 5.90$, $p < .01$, such that the locus effect was highly significant for Pathway 1: $F(2, 25) = 12.14$, $p < .001$; P1, 40.86 (22.81), H1, 26.43 (21.34), and C1/C2, 17.00 (21.96) for Loci 1, 2, and 3 respectively; but not for Pathway 2, $F(2, 26) = 1.65$, *ns*, though the ratings declined across the loci even in this pathway: P2, 43.57 (17.37), H3, 38.57 (23.16), and C4, 36.00 (28.64). In addition, a follow-up analysis showed that the mean impact for C1 and C2 was approximately half that for C4, $F(1, 13) = 7.51$, $p < .025$.

$p < .01$, and a three-way interaction between condition, pathway, and locus, $F(2, 96) = 9.66$, $p < .001$. There were no other effects.

As expected a follow-up ANOVA on Pathway 1, with the between-subjects factor of condition and the within-subjects factor of locus, showed a significant interaction between condition and locus, $F(2, 96) = 4.36$, $p < .01$. Locus was significant in the direct percentage condition, $F(2, 48) = 9.93$, $p < .0001$, but was not significant in the indirect percentage condition, $F = 1.02$, *ns*. Further analysis of the ratings in direct percentage condition confirmed a significant linear decline in judged impact, $F(1, 24) = 17.22$, $p < .001$. The quadratic (U-shaped) trend evident in these data was also significant, $F(1, 24) = 19.23$, $p < .001$. The difference in rated impact between populations at two- and three-links distance was greater than that between populations at one- and two-links distance.

A similar ANOVA within Pathway 2 showed that condition interacted with locus in that pathway too, $F(2, 96) = 3.55$, $p < .05$. There was a marginally significant effect on locus in the direct percentage condition, $F(2, 48) = 3.15$, $p = .052$, largely because of estimates for C4 (Locus 3). But the important point for present purposes is that in the indirect percentage condition, estimates of percentage change did not differ as a function of locus, $F(2, 48) = 2.16$, *ns*.

Follow-up within-subjects analysis of the estimates of the degree of change at Locus 3 (carnivores) in the direct percentage condition showed that these were significantly greater for carnivore C4 in Pathway 2 (43.6%) than the mean of those for C1 and C2 in Pathway 1 (21.1%), $F(1, 24) = 23.25$, $p < .001$. In contrast, for the indirect percentage condition, there was a marginally significant difference in the other direction, $F(1, 24) = 3.36$, $p = .08$: The mean estimates were 57.9% for Pathway 1 compared to 35.0% for Pathway 2.

The mental simulation proposal supposes that impact judgements reflect differences in the envisaged size of the original populations. Data in the indirect percentage condition provide an opportunity to examine this supposition. Individuals were presented with the initial coverage of the plants in square miles (see *Materials*), and so analysis is restricted to the estimates for herbivores and carnivores. It is reasonable to suppose though that individuals assume that there are vastly more plants than there are animals that eat them. An ANOVA of the initial population size estimates with the within-subjects factors of population level and pathway confirmed that the mean estimates of the herbivore population were significantly greater than the mean estimates for the carnivore populations: 3,879 vs. 1,407, $F(1, 24) = 4.32$, $p < .05$. There was no overall effect of pathway ($F < 1$) and only a marginal interaction between pathway and level, $F(1, 24) = 2.66$, $p = .12$.

A separate comparison off the estimates for C4 (the carnivore in Pathway 2) compared to the mean estimates for C1 and C2 (the carnivores in Pathway 1), confirmed that the initial mean population size for C4 was greater, though not double, that of C1 and C2 taken together, $F(1, 24) = 4.45$, $p < .05$, averaging 1,113 compared to 850. Such an outcome is qualitatively consistent with the finding in the direct percentage condition that individuals judge the impact of change on C4 to be greater than that on C1/C2. Other task-specific factors in the direct percentage condition may affect the precise numerical values.

In summary, the distance effect for impact judgements is task dependent. This outcome refutes the dissipation hypothesis but is consistent with the mental simulation proposal. On this proposal, individuals mentally simulate change by taking a constant proportion of the original population sizes that themselves decline across the levels considered here. In consequence, impact judgements based on these numbers also decline across levels. A distance effect was observed then when judgements were made as per White (1997, 2000), though it was strongest for Pathway 1 (see Footnote 1). A distance effect was also observed, at least in Pathway 1, even when individuals were asked to estimate impact in terms of the percentage change to the populations (direct percentage condition), presumably because judgements were based on the product of the simulation and not on how these were computed. No distance effect was observed in the indirect percentage condition because in that condition estimates of percentage change were computed from the recorded amount of change (which differed across population levels) and the recorded original population estimate.

At a minimum the data in indirect percentage condition are consistent with the notion that in mentally simulating impact individuals maintain the same population ratio. However, this does not imply any deep and explicit understanding of ecological principles. It simply reflects the outcome of a cognitively efficient procedure ("make the same proportionate change") for meeting task demands. The next study seeks more direct evidence of the potential richness of individuals' causal understanding of change.

EXPERIMENT 3

Green (1997, Experiment 1; see also Green, 1992) required individuals to explain a cyclic rise and fall in a population of foxes in Northern Canada. In Green (1997), individuals typically explained the cyclic data pattern in terms of a cyclic change either in some external factor (e.g., harsh winters, over-hunting by man) or in some internal factor (e.g., the fertility of the foxes themselves). Such accounts are simple and sufficient given the presented data. Individuals rarely proposed that the population cycle of foxes reflected the two-way causal interaction of foxes and their prey. On such an account an increasing population of prey leads to an increase in the size of the fox population, which leads to a progressive reduction in the number of prey and a fall in the fox population, which in turn enables a gradual increase in the prey population and so on.

In the present study, individuals were required to explain a pattern of change to one of the populations in a microworld as the system moves towards a new stable level under a smooth increase in temperature. Imagine a microworld comprising a plant P, a herbivore, H, and a carnivore, C. Figure 2 depicts a pattern of change to the population H.

Such a pattern of change, unlike that in Green (1997, Experiment 1) does not admit to a simple explanation in terms of cyclic changes in some external or internal factor. A one-way causal account provides a simple account if one just considers the beginning and the end points of the pattern and treats as noise the variations in the transition to a new equilibrium. According to such an account the gradual increase in temperature leads to an increase in the plant P eaten by the herbivore H and so allows for gradual expansion in the numbers of H. Alternatively, if individuals treat the variations in the transition to a new equilibrium as data to be explained, a two-way causal account offers the simplest explanation because it avoids the need to postulate a number of arbitrary and ad hoc changes based, for instance, on variations in the fertility of the herbivores. A two-way causal account might explain the initial increase in the herbivore population by virtue of an increase in the plant eaten by the herbivore. A temporary decline in this population might then arise because of an increase in the carnivore population C occasioned by this increase in H. A decline in H has the consequence of increasing the amount

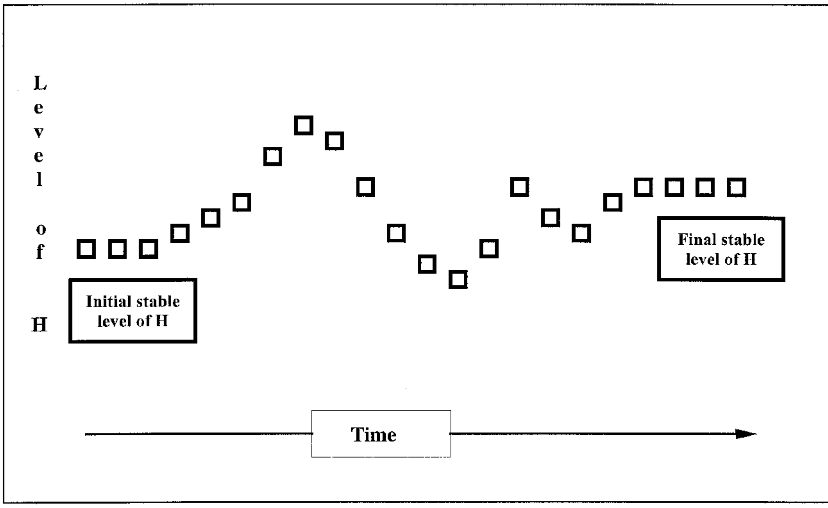

Figure 2. Pattern of changes to the size of the H population in Experiment 3 as the microworld reaches a new stable level for each population of plant and animal. Each square is one time unit.

of the plant P and decreasing the carnivore population. Such circumstances allow the herbivore population to increase once more.

What factor or factors may affect the accounts proposed? One possibility is that individuals are unable to handle the complexity of the system described and so construe the data as a noisy trend towards a new equilibrium state. White (2000) has suggested that two-way causal reasoning may be possible when a microworld involves just two population levels (e.g., herbivores and carnivores) as in Green (1997, Experiment 4) but not otherwise. On this view, only one-way causal accounts will be proposed in the present study as the microworld involves three population levels. Certainly, in other circumstances, such as cross-series forecasting (Harvey, Bolger, & McClelland, 1994), individuals employ heuristics that reduce the computational difficulty of the task.

However, an individual's mental model of relations in the microworld may be more pertinent to how they explain the data. In order to examine this possibility, an initial phase of the present study required individuals to depict the relations between entities in the microworld using relations such as "eats" or "supports" as "H eats P" or "P supports H". The expectation was that some individuals would depict unidirectional connections amongst the populations, whereas others would depict bidirectional connections and indicate, for instance, that carnivores eat herbivores and also that herbivores support carnivores. Unidirectional connections in the diagram were taken to imply a mental model with one-way causal relations amongst populations, whereas bidirectional connections in the diagram were taken to imply a mental model involving two-way causal relations amongst populations. The prediction tested was that individuals who represented bidirectional connections in the initial phase, compared to those who represented unidirectional connections in the initial phase, would be more likely to account for the pattern of change in terms of two-way causal processes.

Such a prediction follows if the initial mental model constrains individuals' perception of the data to be explained. Alternatively, individuals with one-way causal relations in their initial mental model (i.e., those with unidirectional connections in their diagrams in the initial phase) may recognize that their mental simulation based on this model does not fully account for the pattern of data and so flesh-out their mental model in terms of explicit two-way causal relations. In this case, the initial mental model (as inferred from the participants' diagrams) would only weakly constrain explanations of the pattern of data, and two-way causal accounts would predominate.

Method

Participants

Participants were 79 applicants for places on the undergraduate programme at UCL (22 males, 57 females) modal age 18 years, range 17–21 years.

Design and procedure

The study consisted of two phases. The initial phase required individuals to represent the connections between the elements in the microworld using one or more relations ("eats"/"supports"). The components of the microworld were referred to using single letters: W (weather), P (plant), H (herbivore), C (carnivore). The letters depicting these elements were printed either linearly or in a circle. Individuals were assigned at random to one of these two formats. In fact there was no effect of format on the representations, and so this variable will not be considered further. Having completed their representation of the relations in the microworld, participants turned to the next page in the booklet, in order to complete the second phase of the study, and wrote down their explanation for the pattern of changes to the size of the H population. Other aspects of the procedure were as before.

Materials

Participants were asked to imagine a microworld described exactly as follows:

> Plants P grows best under warm conditions.
> Animals H eat plants P only.
> Animals C eat animals H only.

In the first phase of the study, participants were asked to indicate connections as they saw them between the weather (W), plants (P), and animals (H and C) in this microworld by drawing lines connecting the letters. Different lines depicted the different causal relations of "support" (an arrow-headed line), "eating" (a line with a filled stop at the end), and "reproduction" (an arrow-headed line pointing back on itself). Individuals also labelled each included line with the appropriate verb. The instructions for the second phase of the study (on the following page of the booklet) read as follows:

> Imagine now a climate change such that the microworld becomes smoothly a little warmer over the course of three time units and then stays stable at this new temperature from then on. The graph below depicts changes in the population level of animals H as the populations of plants and animals move to a new stable level, i.e., naturally maintain themselves at that size, year after year, barring outside interference.
>
> How might the *pattern* of changes to a new stable level of population best be explained in your view? If more than one explanation occurs to you, please write that down too.

The graph depicted in Figure 2 was presented at this point, and individuals wrote down their explanation of the pattern immediately below it.

Treatment of data

The experimenter coded the diagrams for the initial phase of the study in terms of whether or not individuals represented a unidirectional connection between plants, herbivores, and carnivores (i.e., whether they used labelled lines indicating that herbivores eat plants and carnivores eat herbivores) as per the description of the microworld or represented bidirectional connections and so also used the relation of "supports" indicating not only that H eats P but also that P supports H and that C not only eats H but that H also supports C. All participants used the relation of support to describe the relationship between the weather and plants (P).

Separately, and independently of the coding of the diagrams, explanations in the second phase of the study were coded in terms of their causal content according to the following, pre-defined scheme.

One-way causal accounts: Individuals referred to the increase in temperature increasing the number of plants and in consequence the number of H animals.

Two-way causal accounts (two-level): Individuals referred to temperature increasing the number of plants (P) and then explained the pattern in one of two ways: (1) a two-way interaction between the herbivore population (H) and the plant population (P) such that an increase in P leads to an increase in H, which leads to a small decrease in P and so a small decrease in H before P recovers to a higher level, and so on or (2) an analogous two-way interaction between the herbivore population (H) and the carnivore population (C).

Two-way causal accounts (three-level): Individuals referred to temperature increasing the number of plants (P) and then explained the pattern of change in terms of a two-way interaction between the herbivore population (H) and the plant population (P) and a two-way interaction between the carnivore population (C) and the herbivore population (H).

Other accounts: These were defined by exclusion and, in fact, offered mere descriptions of the data.

Results and discussion

Table 3 displays the number and percentage of participants providing each type of account for the pattern of change to the population of herbivores as a function of their initial representation of the relations in the microworld as depicted in the first phase of the study. Overall 63%

TABLE 3
Experiment 3: The frequency and percentages of different types of causal account of the pattern of the herbivore population change as a function of the initial representation

	Type of causal account							
			Two-way					
	One-way		*2level*		*3-level*		*Other*	
Initial representation	*Freq.*	*%*	*Freq.*	*%*	*Freq.*	*%*	*Freq.*	*%*
Unidirectional[a]	16	32	24	48	2	4	8	16
Bidirectional[b]	5	17	19	66	5	17	0	0

[a] $N = 50$.
[b] $N = 29$.

(50/79) of participants proposed two-way causal accounts of the changes to H, $z = 2.25$, $p < .025$, binomial test. This study therefore provides evidence that a substantial number of individuals construct two-way causal accounts in order to explain a specific pattern of change even for a microworld involving three population levels (cf., Green, 1997, Experiment 4). However, few individuals (9%; 7/79) envisaged two-way causal processes involving all three populations in the microworld.

Consistent with expectation, one-way causal accounts were more common amongst participants who represented unidirectional connections between P and H and between H and C in the first phase of the study than amongst participants who represented bidirectional connections in that phase (48%; 24/50 vs. 17%; 5/29). A chi-squared test of the data in Table3 (summing over the types of two-way causal account), yielded $\chi^2(2, N = 79) = 6.96$, $p < .01$. Excluding accounts in the other category yielded $\chi^2(1, N = 71) = 2.77$, $p = .10$.

The initial representation of relations therefore did not strongly constrain causal accounts of the pattern of change. In fact, over half of the participants who represented unidirectional connections in the first phase of the study went on to construct two-way causal accounts of the pattern of change to H in the second phase of the study. Such an outcome is consistent with the notion that individuals elaborate their mental models in order to simulate a better fit to the data to be explained.

GENERAL DISCUSSION

The aim of these studies was to contrast two views on the nature of causal thinking about ecological problems. The first, proposed by White (1997, 2000), supposes that naïve individuals approach such problems either by using an abstract causal principle or by applying a force-resistance analogy to the problem. In either case causal effects are presumed to be one way and to decrease with distance from the source of the perturbation. According to this dissipation hypothesis, causal judgements will show a distance effect: Both the judged causal likelihood of an action achieving a target effect and the judge causal impact of a perturbation will decline with distance from the source of the perturbation.

The alternative view is that individuals build specific mental representations or mental models of the problem domain (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991) and mentally simulate the effects of change (Kahneman & Tversky, 1982). On this mental simulation view, the distance effect obtained by White (1997, 2000) is task specific and reflects the judgements that individuals reach given the specific mental simulations elicited by the task. We review the main findings and their interpretation.

Experiment 1 confirmed a distance effect in the ratings condition (as used by White, 1997) in which individuals were required to judge the causal likelihood that different control actions (e.g., changing the amount of a plant) will achieve a target effect (i.e., changing a population of carnivores by a stable amount). But contrary to the dissipation hypothesis, the no ratings condition, in which individuals were required to identify a single control action that would change the carnivore population, revealed no distance effect. Indeed individuals tended to select climate (the technically correct solution) as the factor to control. Experiment 1 therefore showed the distance effect to be task dependent consistent with the predictions of the mental simulation proposal.

In the ratings condition, individuals must perform a number of different simulations in order to evaluate the relative causal likelihood of different control actions achieving the target effect (e.g., controlling the weather vs. controlling the size of the herbivore population). Different numbers of populations intervene between a designated control action and the target effect. In searching for a basis on which to judge the causal efficacy of different control actions (a task in which there is a pragmatic presumption of differential efficacy), the number of intervening populations provides a metric of possible disabling conditions (Cummins et al., 1991)—conditions that could derail the causal sequence.

Individuals in the no ratings condition need only mentally simulate a causal sequence sufficient to generate the causal effect. Amongst the causal relations explicitly encoded in the mental model (climate to plant; plant to herbivore and herbivore to carnivore), it appears that individuals treat climate as causally prior. They may do so because of background knowledge or because, as part of their mental simulation, they reason backward from the target effect to a possible factor to control, and climate is at the end of this causal sequence. There is no evidence that individuals spontaneously engage in counter-factual thinking in this condition and consider which other populations could be controlled. If they had done so, their results would have been more like those in the ratings condition. In line with the proposals of McEleney and Byrne (2000), causal thinking does not necessarily engage counter-factual thinking.

Experiment 2 examined judgements of the impact of a small change in temperature on each of the populations in the microworld and contrasted two conditions: an indirect percentage condition and a direct percentage condition. As expected, judgements in the direct percentage condition decline significantly with distance at least in one of the causal pathways (see also Footnote 1) in line with the findings of White (1997, 2000). However, contrary to the dissipation hypothesis, but consistent with the mental simulation proposal, there was no distance effect in the indirect percentage condition. In this condition, individuals explicitly estimated the initial population size and the amount of change (impact). The percentage change computed from these figures was a constant proportion of the initial population size.

On the mental simulation proposal, individuals are held to simulate change by taking a constant proportion (purely for reasons of cognitive economy) of the tokens representing different populations. In consequence, when they are required to estimate the size of the initial, and subsequent, populations (the indirect percentage condition), the computed percentage change does not differ across population levels. In the direct percentage condition, the outcome is different because in this case individuals must mentally recall their initial representation in order to compute the percentage change. Either because of memory constraints or because of the pragmatic demand of the task that warrants different responses, individuals focus on their current representations. As they represent more tokens of plants than tokens of herbivores and more tokens of herbivores than tokens of carnivores in their initial mental models (Experiment 2 provided a measure of support for this claim) impact judgements based on the *number* of population tokens post simulation decline with distance from the source of the perturbation.

The task-dependent nature of the effects observed in Experiments 1 and 2 refute the dissipation hypothesis. A further problem with the hypothesis is that it has no mechanism to explain, even in principle, how individuals construct two-way causal accounts of a phenomenon. Experiment 3, however, showed that a significant number of individuals do construct such accounts in order to explain a pattern of change.

Experiment 3 asked individuals to explain a pattern of change in the size of a herbivore population H as it moved towards a new level of population stability under a smooth increase in a change in temperature. According to the mental simulation proposal individuals attempt to simulate the pattern of change based on their initial mental model of the microworld but they can elaborate this initial model in order to achieve a better fit. In order to gain an idea of the nature of the initial mental model, individuals in the first phase of the experiment were required to depict the causal connections amongst the entities in the microworld. This phase distinguished individuals whose initial representation was unidirectional (e.g., herbivore H eats plant P, carnivore C eats herbivore H) from those whose initial representation was bidirectional (e.g., H eats P, and P supports H).

The supposition was that unidirectional connections indicate one-way causal relations in the mental model, whereas bidirectional connections indicate two-way causal relations. Overall, the nature of the initial representation (unidirectional or bidirectional) did co-vary with the nature of the accounts produced. Two-way causal accounts were more common given a bidirectional initial representation. But there was no strong coupling. Individuals appear to adapt or change their initial model (cf., Clement, 1993; Johnson-Laird & Byrne, 1991) so that it yields a more or less better fit to the actual data. Over half the individuals with unidirectional connections in the first phase and, by inference, one-way causal mental models produced two-way accounts of the pattern of population change in the second phase.

In order to construct such an account, individuals need to flesh-out their mental models of the entities and their relations and examine the consequences, for instance, of an increase in the population of H on P and the effect of this change on H at a later point in time. Two-way causal interaction amongst the entities does yield variations in the size of H and provides a simple account that fits the data. The data suggest that even when individuals do initially represent the bidirectional nature of relations that they may first explore an outcome involving a one-way causal process (17% of individuals produced one-way causal accounts despite a bidirectional initial representation). For most individuals though, the insufficiency of a one-way causal account appears to prompt the search for a more complex account. It follows that the initial mental model does not fully determine the perception of the pattern to be explained. From an adaptive point of view this is clearly important.

The mental simulation that underlies the written accounts or abductive explanations of change is presumably constrained by the capacity of working memory. Conceivably two-way causal accounts involving all three population levels in the microworld are rare (just 9% of the sample) because the mental simulation required exceeds the working memory capacity of most participants. In contrast, two-way causal accounts involving just two population levels are within the capacity of the majority at least when the microworld is relatively simple. Only further research can determine this matter as no individual difference measures were taken.

A critical further feature of the present proposal is that mental simulation ceases when there is an adequate fit between the outcome of the simulation and the actual pattern of data. This entails, to reiterate a point made earlier, that individuals do not spontaneously consider alternative causal processes when the fit is deemed adequate.

One way to explore this claim is to allow individuals to interact with an actual external simulation of change in the microworld based on their own accounts of the change. They can then compare explicitly the pattern of data generated by their own understanding of the microworld with the presented pattern of data. It will then be possible to explore more directly the psychological processes underlying abductive explanation and to ascertain whether or not considerations other than sufficiency are operative (cf., Green, 1999; Josephson & Josephson, 1996). This proposed line of research also links research in the domain of ecological understanding to research on the relationship between learning to control a system and the understanding of it (e.g., Berry & Broadbent, 1984, 1988; Geddes & Stevenson, 1997).

In conclusion, judgements of causal likelihood and causal impact concerning change in a microworld are task dependent. It is proposed, therefore, that distance effects emerge in certain judgement tasks because individuals mentally simulate effects rather than because of any assumption that causal effects dissipate with distance or because of the application of a force-resistance model. The potential richness of individuals' causal understanding is better revealed in their accounts of change. Two-way (interdependent) causal accounts emerge as a consequence of thinking through causal effects during the mental simulation of change.

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