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Naive Analysis of Food Web Dynamics: A Study of Causal Judgment About Complex Physical Systems

PETER A. WHITE

Cardiff University

When people make judgments about the effects of a perturbation on populations of species in a food web, their judgments exhibit the dissipation effect: a tendency to judge that effects of the perturbation weaken or dissipate as they spread out through the food web from the locus of the perturbation. In the present research evidence for two more phenomena is reported. Terminal locations are points in the food web with just a single connection to the rest of the web. Judged changes tended to be higher for species at terminal locations than for species the same distance from the perturbation but at nonterminal locations. Branches are points in the web where a route splits into two or more routes. Judged changes tended to be lower for species following branching points than for species the same distance from the perturbation but not following branching points. It is proposed that the findings can be explained as effects of a mental model employing concepts of influence and resistance. Under this model a perturbation is a change in energy level at a point in the system that acts as an influence affecting the rest of the system. The basic concepts in this model are domain-general and on that basis it is predicted that the dissipation effect should be found in judgments of any physical system to which notions of influence and resistance can be applied.

I. INTRODUCTION

In recent years, there has been considerable progress in research on causal cognition. Much has been discovered about the development of causal understanding and judgment and its involvement in many cognitive domains. Most of this research has looked at judgments about single cause-effect relations in isolation. In reality, individual causal relations are not isolated from each other but tend to be linked in dynamic systems. Causal cognition involves not just identifying the cause of some effect, but also integrating

Direct all correspondence to: Peter A. White, School of Psychology, Cardiff University, P.O. Box 901, Cardiff CF11 3YG United Kingdom; E-mail: whitepa@cardiff.ac.uk.

collections of individual events into an organized representation of chains and networks of causal relations. Understanding how events fit together is as important to our comprehension of reality as understanding individual causal relations is. Yet there has been comparatively little research on causal cognition at this level of analysis.

Progress has been made in elucidating the naive understanding of particular systems, such as the causes of examination failure or interactions between factors involved in personal debt (Brickman, Ryan & Wortman, 1975; Kelley, 1983; Kempton, 1986; Lunt, 1988, 1991; Lunt & Livingstone, 1991; White, 1992a, 1995a), but the daunting complexities and individual characters of the systems investigated mean that the findings tend to have limited or uncertain generalizability. However, a recent series of experiments has uncovered a phenomenon that might reflect a general feature of the naive understanding of causal interactions in complex physical systems, the dissipation effect (White, 1997, 1998, 1999).

The dissipation effect has mainly been studied in judgments made about food web dynamics. A food web is a trophic structure of species in a community: food webs map connections between the species according to their feeding relationships (Ricklefs, 1993). The effect on the whole web of a perturbation, a sudden significant change to a part of it, is mediated by the structural features of the web. Researchers have found it difficult to predict the effects of such perturbations because of the great complexity of possible interactions, and food webs can exhibit chaotic behavior following a perturbation. Nevertheless it is generally agreed that natural food webs tend to be stable because unstable trophic structures tend, almost by definition, to be short-lived. In addition there are many factors that promote stability in predator-prey relationships, and therefore in the food web as a whole. Stability in a population does not mean an absence of change. As Pimm (1982) defined it, stability means "that population densities return to an equilibrium following a perturbation" (p. 11). Ricklefs (1993) drew particular attention to the number and pervasiveness of processes that maintain and restore equilibria. Summarizing the research literature at that time, Pimm (1982) said, "nearly all populations are characterized by patterns of change that keep their numbers within bounds. . . densities tend to return to a recognisable equilibrium level or, more rarely, a cyclical pattern. Only a minority of populations fluctuate so wildly that an equilibrium level is not obvious" (p. 11).

White (1997, 1998, 1999) found that lay people do not share this understanding of the maintenance and restoration of equilibria in food webs. Instead, they tend to judge that population levels undergo lasting changes following a perturbation: that the greatest change will be observed in species closest to the perturbation and the least in species furthest away. This is the dissipation effect. Distance from the perturbation is defined in terms of the structure of the food web: the distance of a species from a perturbation is the minimum number of links that must be traversed to get from the perturbation to the species. This can be explicated with the aid of the model food web depicted in Figure 1, which was used by White (1997).

In this food web there are two species of plants. One species prefers warm and dry conditions and the other prefers cool and wet conditions, and the two species compete for space. There are three herbivores that eat the plants and four carnivores that eat the

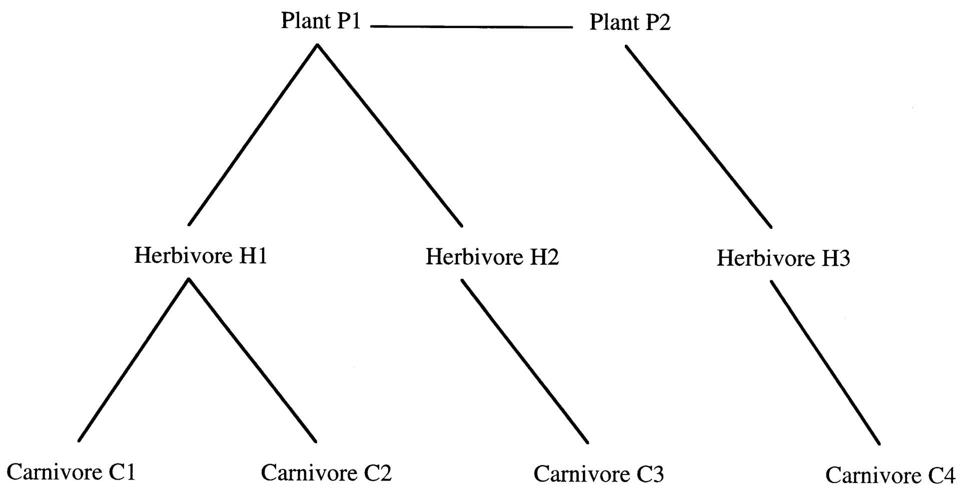

Figure 1. Model food web used by White (1997).

herbivores. Figure 1 depicts the set of feeding relationships between these nine species. Suppose there is a perturbation that affects carnivore C1. Then herbivore H1 is at one link distant, plant P1 and carnivore C2 are both at two links distant, plant P2 and herbivore H2 at three links distant, and so on. In some food webs, there is more than one possible route between species; in such cases distance is defined as the shortest possible route (White, 1998). The measure in tests of the dissipation effect is judged change for a given number of links distant from the perturbation. If there is more than one species at a given number of links distant, the measure is the mean of the judged changes for those species.

In one problem in White (1997) participants were told that, over a period of years, the climate gradually became warmer and drier. This is a perturbation that most directly affects the two plant species, which are therefore both at one link distant from the perturbation. Given the structure of the food web in Figure 1, all of the herbivores are at two links distant and all of the carnivores at three links distant from this particular perturbation. Participants estimated the effect of the climate change on the populations of all the species. The biggest estimated effects were found for the two plant species. Smaller changes were estimated for the herbivores: increases for those that ate the plant that benefited from the climate change and decreases for those that ate the other plant. Smaller changes still were estimated for the carnivores, with increases for species that predated herbivores that ate the plant that benefited from the change and vice versa for the others. Thus, the effect of the change in climate was judged to dissipate with increasing distance from the location of the perturbation.

Experiments have so far shown the dissipation effect to be robust but have not succeeded in explaining why it occurs. In the initial study, White (1997) set four problems involving perturbations to different loci in the food web shown in Figure 1 and found evidence for dissipation in all of them. White (1998) reported three experiments. In Experiment 1 dissipation was found to occur in a food web with different properties from that used by White (1997), including omnivorous relations that considerably complicated the structure of the food web. In Experiment 2 dissipation was found to occur in reasoning about a model of a real food web. This experiment also found evidence for dissipation in the absence of changes in participants' ratings of confidence in their judgments, implying that changes in confidence do not account for the dissipation effect. In Experiment 3 dissipation was found to occur in judgments about a different type of physical system based on the hydrological cycle, suggesting that the dissipation effect may be a general feature of judgments about complex physical systems.

White (1999) also reported three experiments. In Experiment 1 the dissipation effect was not affected by presence or absence of a diagram of the food web nor by whether participants were asked to judge change after one year or ten years. In Experiment 2 the structure of the food web was dissociated from the number of links in a causal chain between the perturbation and the species being judged. For example in one condition participants judged the effect of a change at species 1 on species 2, the effect of the change to 2 on 3, to 3 on 4, to 4 on 5, to 5 on 6, and to 6 on 7. In another condition participants judged the effect of a change at species 1 on species 2, the effect of the change to 2 on 3, to 3 on 4, to 4 on 3, to 3 on 2, and to 2 on 1. Each sequence of judgments constitutes a causal chain of six links. However, in the former chain, the final judgment concerns a species six links distant from the perturbation, whereas in the latter chain the final judgment concerns a species zero links distant from the perturbation: in this way, causal chain length is dissociated from number of links distant in the food web. The dissipation effect was found in the former condition but not in the latter condition, showing that it is associated with the structure of the food web, not with the number of steps in a chain of causal inferences. In Experiment 3 participants were asked to judge effects on all species in a web at each of several time periods following a perturbation. The effect was strongest in judgments about time periods soon after a perturbation, but did not entirely disappear even in judgments about time periods relatively long after the perturbation.

White (1999) was forced to conclude that a full explanation of the dissipation effect still awaits elucidation. The findings do offer some clues, however. Although introducing omnivores did not eliminate the dissipation effect (White, 1998, Experiment 1) it certainly had a significant effect on causal judgment (described in more detail below). The dissipation effect was shown to be associated with the structure of the food web and not with causal chain length (White, 1999, Experiment 2). It also generalized to a different kind of physical system, the hydrological cycle (White, 1998, Experiment 3). These clues all suggest that the structure of the physical system is a primary determinant of amount of judged change. The present research investigates this possibility further with the principal aim of formulating and testing a hypothesis that can explain the observed effects.

If the dissipation effect is attributable to structural features of physical systems then two things should follow. First, it should be robust across different features of content. Content features have already been manipulated in some of the experiments with little effect. In the present research Experiment 1 manipulates problem content in so far untried ways to obtain further evidence about the robustness of the phenomenon. Second, features of food web structure other than distance from a perturbation may also have effects on

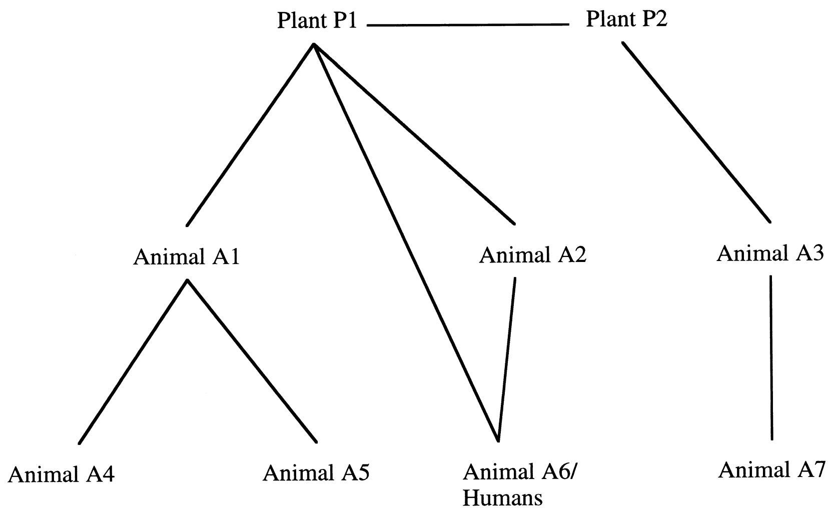

Figure 2. Model food web used in Experiment 1.

causal judgment. For this reason, findings of the research so far reported are scrutinized for evidence of other effects of structure, and this evidence is used to formulate hypotheses that are tested in the remaining experiments. An additional role for Experiment 1 in this paper, therefore, is to contribute to the planned scrutiny of evidence.

II. EXPERIMENT 1

The basic food web for Experiment 1 was a modified version of the original model food web used by White (1997) and is shown in Figure 2. A link has been added between plant P1 and what was formerly carnivore C3, which in this experiment is identified as either animal A6 or humans, depending on condition.

White (1995a) ran a study in which participants were presented with 12 descriptors, including four human descriptors (e.g., human population level), four plant descriptors, and four animal descriptors. They were asked to judge whether each of these would affect each of the remainder, and from their judgments a causal network was constructed following the method pioneered by Lunt (1988). The causal network that emerged was markedly unidirectional and human descriptors tended to lie at the top of the network. In other words, humans were judged to affect plants and animals, but not to be affected by them. Animals, by contrast, tended to lie near the bottom of the network and to have little effect on humans and plants, but to be affected by them.

These findings suggest that the amount of change judged to occur at a given location in a food web may depend on whether that location is occupied by an animal species or by humans. If there is a perturbation one link distant from this location then under the usual tendency to the dissipation effect a relatively large amount of change would be judged to occur. But if the location is occupied by humans then the findings of White

(1995a) support a prediction that little change will be judged to occur, and in consequence that the dissipation effect would be eliminated or even reversed. This reasoning is tested in Experiment 1.

The content of the perturbations may also have an effect. Perturbations used so far have concerned more or less natural changes to populations, such as effects of disease. The classic example of a perturbation that had an effect opposite to dissipation, however, is the DDT saga documented by many authors (e.g., Ricklefs, 1993; White, 1997). This exemplifies pollution with a human-manufactured chemical. A perturbation of this kind has yet to be investigated in any experiment on the dissipation effect. It is possible, however, that the widespread publicity given to pollution incidents such as DDT means that people understand something of the scale and complexity of the interactions that can occur following the introduction of pollutants into ecosystems. Thus, while they may judge dissipation to be a natural effect of natural perturbations, they may not judge dissipation to be a natural effect of pollutant introductions. This possibility will be tested in Experiment 1 by comparing the judged effects of perturbations due to natural occurrences and pollution incidents.

Method

Participants

The participants were 80 undergraduate students of subjects other than psychology.

Materials

The model food web used in this experiment is shown in Figure 2. All participants received a general information sheet, which they retained throughout the experiment. They were asked to imagine an area of the natural environment of a few square miles. Participants in the “animal” condition were then given the following information about the species in the area.

Plant P1 thrives best under warm temperatures and low rainfall.
Plant P2 thrives best under cool temperatures and high rainfall.
Plants P1 and P2 compete for space: the more space one has, the less the other has.
Animal A1 only eats plant P1.
Animal A2 only eats plant P1.
Animal A3 only eats plant P2.
Animal A4 only eats animal A1.
Animal A5 only eats animal A1.
Animal A6 only eats plant P1 and animal A2.
Animal A7 only eats animal A3.

In the “human” condition, instead of the information about animal A6 the following information was given: “The humans only eat plant P1 and animal A2.” Participants also received and retained throughout the experiment the diagram of the food web shown in

Figure 2. Participants in the animal condition saw only animal A6 in the "animal A6/humans" location; participants in the human condition saw only humans.

Four written problems were then presented, always in the same order.

Problem 1: Animal A6/Human + 100%. Participants in the animal A6 condition were told to imagine that the population of animal A6 doubles in size—that is, increases by 100%. Participants in the human condition were told to imagine that the human population doubles in size. All were asked to judge what effect, if any, the increase in size of (whichever) population would have on the populations of the other species in the area. As in previous experiments (White, 1997, 1998) they were instructed to judge the likelihood of a stable change only, meaning a change that would naturally maintain itself year after year, once there has been time for it to get established, and assuming nothing else interferes with it.

For the rating task, they were given a population descriptor, such as "population of plant P1," accompanied by the three alternatives "increase," "decrease," and "no change." They were instructed to underline one of these. They were further instructed that, if they had underlined "increase" or "decrease," they should then write in a score from 1 to 100 indicating the amount of the judged change: "the bigger the change you think will occur, the higher the number you should put." They were told that they did not have to do this if they underlined "no change." They were to make this judgment for each of the species in the area apart from the perturbed species.

In problems 2, 3, and 4, everything was identical for the animal A6 and human conditions except for the presence of animal A6 in one and humans in the other. The remaining problems were all presented in two forms, one depicting a natural perturbation (the "natural" condition) and the other a perturbation due to human interference (the "unnatural" condition).

Problem 2: Animal A5 − 100%. In the natural condition participants were first instructed to forget about the Problem 1 perturbation and imagine that everything was as it had been originally. They were then told to imagine that all members of animal species A5 leave the area permanently, so that the population of animal A5 in the area is zero. Instructions in the unnatural condition were the same except that participants were told to imagine that a factory accidentally spills a chemical that is toxic to animal A5 and wipes that species out completely, so that the population of animal A5 in the area is zero. They were told that the chemical is not toxic to any other species. In both conditions participants were then instructed to judge what effect, if any, the disappearance of animal A5 from the area would have on the populations of the other species in the area. The remaining instructions were as in problem 1.

The actual perturbation, the complete disappearance of A5 from the area, is the same in both conditions: only the cause of the perturbation is different.

Problem 3: Plant P1 − 50%. Participants were first instructed to forget about the Problem 2 perturbation and imagine that everything was as it had been originally. Participants in the natural condition were then told to imagine that plant P1 undergoes a rapid natural decline to half its former level—in other words, the population of plant P1 decreases by 50%. Instructions in the unnatural condition were the same except that participants were told to imagine that a virus genetically engineered by humans is introduced to the area. The virus infects plant P1 and reduces its population to half its former level—in other words, the population of plant P1 decreases by 50%. They were told that all other species are naturally immune to the virus. In both conditions participants were then instructed to judge what effect, if any, the 50% decrease in the population of plant P1 would have on the populations of the other species in the area. The remaining instructions were as in Problem 1. As in Problem 2, the actual perturbation is the same in both conditions and only the cause of the perturbation is different.

Problem 4: Plant P1 Toxic. Participants were first instructed to forget about the Problem 3 perturbation and imagine that everything was as it had been originally. Participants in the natural condition then saw the following information:

> As you may know, some plant species protect themselves from being eaten by having natural chemicals that are toxic or unpleasant to animals. Now imagine that plant P1, which formerly had no such chemical, now acquires a natural chemical protection which is potentially toxic to all living things in the area. (The way in which this would happen is that a strain of the plant that has the chemical gradually replaces the one that doesn't because it has better ability to survive, but you needn't worry about the technicalities of this.) If animals eat P1, levels of the chemical gradually accumulate in their fatty tissues and, the greater the level of the chemical, the more likely the animal is to die. The chemical remains in the animal's tissues until after it has died.

Participants in the unnatural condition saw the following information:

> Now imagine that humans in areas bordering the one we're looking at have been spraying a manufactured chemical pesticide on their land. As it happens the chemical is potentially toxic to all living things in our area. The chemical seeps through the soil into our area and plant P1 takes the chemical up into its tissues through its roots. If animals eat P1, levels of the chemical gradually accumulate in their fatty tissues and, the greater the level of the chemical, the more likely the animal is to die. The chemical remains in the animal's tissues until after it has died.

In both conditions, participants were then instructed to judge what effect, if any, plant P1's chemical protection would have on the populations of the other species in the area. The remaining instructions were as in Problem 1. The information about the toxicity of the chemical and its possible passage through the food web is the same in both conditions: only the origin of the chemical (natural mutation versus human intervention) is manipulated.

Design

Each problem was analyzed separately. The number of links distant from the perturbation was worked out for each species within each problem using the method described in the introduction. There were four different numbers of links (from one to four) in Problem 1, 5 in Problem 2, 3 in Problem 3, and 3 in Problem 4. Animal A6 versus human and natural versus unnatural were orthogonal between-participant manipulations with equal numbers of participants in each condition.

In Problem 1, the design was therefore a 2 (species, animal A6 versus human) × 2 (perturbation, natural × unnatural) × 4 (number of links distant from perturbation) mixed design analysis of variance. There was no manipulation of natural versus unnatural in this problem so no effect is predicted, but the factor enters the analysis because the participants are differentiated by other materials in the experiment. In Problem 2, the design was a 2 (species, animal A6 versus human) × 2 (perturbation, natural versus unnatural) × 5 (number of links distant from perturbation) mixed design analysis of variance. In Problems 3 and 4, the design was a 2 (species, animal A6 versus human) × 2 (perturbation, natural versus unnatural) × 3 (number of links distant from perturbation) mixed design analysis of variance. Comparisons were also planned on mean amount of judged change between animal A6 and humans in Problems 2, 3, and 4, using the t test for independent means.

The dependent measure for these analyses is just the *amount* of change judged to occur: direction of change (increase or decrease) is disregarded. This is in keeping with the analyses performed by White (1997, 1998, in press).

Procedure

Participants were run either singly or in groups of two or three in a comfortably furnished office, supervised by an experimenter. If, in groups, each was seated so that none could see what the others were doing. Each had a work surface so that they could carry out each judgmental task in turn while keeping the species information sheet and the diagram in view. Instructions were all written, so the experimenter gave a brief introduction in which participants were encouraged to ask questions if anything was not clear. When all participants in a given group had finished, the experimenter thanked and paid them. Apart from the information about the role of the diagram participants were not debriefed at the time to avoid any possibility of contaminating future participants. After the conclusion of all the experiments reported here information was posted on a noticeboard reserved for this purpose.

Results

Analysis yielded significant main effects of numbers of links in all four problems. In Problem 1 (A6/human + 100) $F(3,228) = 54.04$, $p < .001$. Paired comparisons with the Newman-Keuls test revealed the order one link > two > three > four, $p < .01$ in all cases. In Problem 2 (A5 – 100) $F(4,304) = 64.02$, $p < .001$. Paired comparisons revealed the order one link > two > three & four & five. In Problem 3 (P1 − 50) $F(2,152) = 32.43$, $p < .001$. Paired comparisons revealed the order one link > two > three, $p <. 01$ in both cases. In Problem 4 (P1 toxic) $F(2,152) = 126.69$, $p < .001$. Paired comparisons revealed the order one link > two > three, $p < .01$ in both cases. Tendencies in all four problems

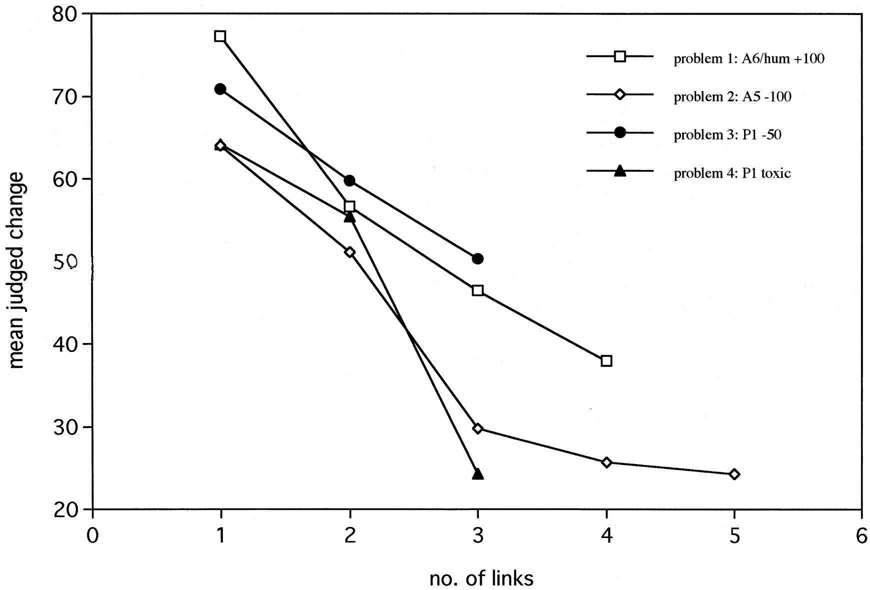

Figure 3. Dissipation effect, Experiment 1.

were consistent with the dissipation effect and offer further evidence of its robustness. The trends for the four problems are depicted in Figure 3. There was no significant effect of or interaction with either the species manipulation or the natural v. unnatural manipulation in any problem.

In problem 3 (P1 − 50) the mean amount of judged change for animal A6 was 68.37 and for the humans was 51.50. These means were significantly different, $t(78) = 2.54$, $p < .05$. A6 and humans are at one link distant from the perturbation in this problem. Although the mean amount of judged change was significantly less for humans, it was not sufficient to produce a significant interaction with the number of links variable. In view of the result of the *t* test, however, a decision was taken to look at the simple effects for the interaction between species and number of links. At one link distant judged change was significantly lower in the human condition than in the A6 condition, $F(1,76) = 4.75$, $p < .05$. This reflects the contribution of the human versus A6 difference found in the *t* test. Comparisons between the human and A6 conditions at two and three links distant were not statistically significant, however ($F < 1$ in both cases). The usual dissipation effect was obtained in both the human and A6 conditions. Far from eliminating or reversing the dissipation effect, therefore, the human versus A6 manipulation has barely affected it.

In Problem 4 (P1 toxic) the mean amount of judged change for animal A6 was 82.37 and for the humans was 56.00. These means were significantly different, $t(78) = 4.39$, $p < .001$. In this problem the interaction between species and number of links was marginally significant, $F(2,152) = 2.69$, $p = .07$. Simple effects analysis was carried out. At one link distant judged change was significantly lower in the human condition than in the A6 condition, $F(1,76) = 5.73$, $p < .05$. This reflects the contribution of the human versus A6

TABLE 1
Mean Judged Change for Left and Right Sides of the Food Web, Experiment 1, Problem 4 (P1 toxic)

	No. of links		
Side of food web	1	2	3
Left	74.62	70.75	—
Right	32.37	24.94	24.31

difference found in the *t* test. Comparisons between the human and A6 conditions at two and three links distant were not statistically significant, however ($F < 1$ in both cases). The usual dissipation effect was obtained in both the human and A6 conditions. This pattern of results closely resembles that in Problem 3.

There was, however, an unpredicted effect of problem content in Problem 4 (P1 toxic). Judged amounts of change were far greater for species on the left side of the food web (species below plant P1 in Figure 2) than for species on the right side (plant P2 and species below that). Means are reported in Table 1. No such difference was observed in Problem 3, which involved a perturbation to the same species. In view of this effect, each side of the food web was analyzed separately. On the left side there are only two different distances from the perturbation. One-way analysis of variance with repeated measures yielded a marginally significant trend in the direction of dissipation, $F(1,79) = 2.81$, $p = .09$. On the right side there are three different distances from the perturbation. Analysis of variance yielded a significant result, $F(2,79) = 12.82$, $p < .001$. Paired comparisons with the Newman-Keuls test revealed the order 1 > 2 & 3. There is therefore some evidence of dissipation on both sides of the web, though it was not as strong as in the other problems.

Discussion

As in previous studies the dissipation effect was found in all four problems. The manipulations of species and perturbation had no significant effect on these trends. In two problems mean amount of judged change was significantly lower for humans than for animal A6, which is consistent with the findings of White (1995a), but in no case did this difference significantly weaken the dissipation effect. In Problem 4 (P1 toxic) a strong effect probably attributable to problem content was found, but this effect did not eliminate the dissipation effect on either side of the web. This experiment has therefore provided further evidence of the robustness of the dissipation effect in the face of manipulations of problem content. The possibility of effects of problem content that would eliminate the tendency towards dissipation cannot be ruled out, but the accumulated evidence of this and other experiments suggests that such effects would be rare at best.

III. RECONSIDERATION OF EVIDENCE

So far, eight experiments have been carried out on the dissipation effect: Experiment 1 above together with one in White (1997) and three each in White (1998) and White

(1999). The evidence points towards an explanation in terms of the structure of the food web but number of links distant from a perturbation is the only structural factor that has been investigated so far. Food webs have many structural features, any of which might influence causal judgment. The remainder of this paper pursues that issue. First, structural features of food webs are identified. Second, evidence for effects of these factors is sought in the eight experiments. Third, the evidence leads to the formulation of three hypotheses. Fourth, preliminary consideration is given to a possible explanatory model. Fifth, three further experiments testing the three hypotheses are reported. Finally, in the general discussion, the explanatory model is further developed.

Structural Features of Food Webs

It may not be possible to draw up an exhaustive list of subjectively salient structural features of food webs: for example, for all we can judge, the ratio of herbivore species to carnivore species might be salient to participants. What follows is a list of the more plausible candidates, with the caveat that there could be others waiting to be discovered. In most cases Figure 1 is used as a guide to illustrate the features.

1. *Trophic level*. In the case of Figure 1, this feature differentiates plants from herbivores from carnivores.
2. *Directionality*. One can identify up (from carnivores to plants) and down directions. Paths from perturbations to particular species may or may not exhibit changes of direction. For example, in Figure 1 the path from C1 to C2 has one change of direction, whereas the path from C1 to P1, the same length, has no change of direction.
3. *Valence*. A judged change following a perturbation can be either an increase or a decrease.
4. *Multiple routes* from perturbation to location being judged. In Figure 1 there is only one linear route, meaning a route that does not involve backtracking, from any location to any other location. In Figure 2, however, there are two routes from plant P1 to animal A6/humans, either directly or via animal A2. Omnivory is a common reason for the existence of multiple routes. An omnivore can be defined as a species that feeds on more than one trophic level (Pimm, 1982), and the presence of omnivores considerably complicates the structure of a food web. Multiple routes can arise for other reasons. For example, with reference to Figure 2, if animal A7 predated animal A2 as well as animal A3, then there would be two routes from plant P1 to animal A7, one via animal A2 and the other via plant P2 and animal A3.
5. *Termini*. In Figure 1, C1 (in fact, each of the carnivores) is at what may be described as a terminus in that it has only one link to the rest of the web. On the other hand, P2 is not at a terminus because it has two links to the rest of the web, to P1 and H3.
6. *Posterior species*. If a species is not at a terminus, then there are, in terms of unidirectional routes, species on the other side of it from a perturbation. These can be called posterior species. For example, if there is a perturbation to P1 in Figure 1, then H1 has two posterior species (C1 and C2), H2 has one (C3), and so on.
7. *Species density*. This refers to the number of species within a given number of links

TABLE 2
Numbers of Higher Means in Paired Comparisons Between Plants, Herbivores, and Carnivores

No. of links	Plants	Herbivores	Carnivores
1	7	1	0
+1	7	8	11

distant from a perturbation. Taking Figure 1 as an example, if there is a perturbation to plant P1, there are three species one link distant from this, H1, H2, and P2, and a total of seven species no more than two links distant (all species except C4). If there is a perturbation to carnivore C2, on the other hand, there is only one species at one link distant, H1, and there are three at no more than two links distant (H1, C1, and P1).

8. *Branches*. Take Figure 1, and imagine again a perturbation to plant P1. In this case the food web branches at H1: in other words, there are two routes out from H1, to C1 and C2. There is no branching at H2, however: the only route out is to C3.

Evidence

Data from the experiments so far carried out were re-examined to seek evidence of possible effects of these structural features. Included in this re-examination were three problems from White (1997), both problems from White (1998, Experiment 2), both problems from White (1999, Experiment 1), the one problem from White (1999, Experiment 3), and all four problems from Experiment 1 above. Excluded were problem 1 from White (1997), because a different kind of dependent measure was used, Experiment 3 from White (1998), because the physical system was not a food web, and Experiment 2 from White (1999), because the food web was a linear chain lacking most of the features examined below. Experiment 1 from White (1998) was included in the examination of multiple routes but excluded from consideration of other features, because the food web had multiple omnivorous relations that make it almost impossible to tease out the effects of other features. Because of the consistency and strength of the dissipation effect, in all comparisons the number of links distant from the perturbation is held constant.

The re-examination of data found no evidence for effects of some of the structural features, specifically directionality, valence, number of posterior species, and species density. For the sake of brevity, this section concentrates on the other four factors.

1. Trophic Level. The experiments included in the re-examination all had three trophic levels, plant, herbivore, and carnivore. Comparisons between pairs of these three at a given number of links distant were listed and in each case the higher of the two means was noted. The numbers of times each kind had the higher of the two means in a comparison were tabulated and the results are shown in Table 2. The distribution of frequencies in this table is statistically significant, $\chi^2(2) = 11.26$, $p < .01$. This result suggests a tendency for greater judged change for plants but only at one link distant from the perturbation. This will be termed the *plant hypothesis* and will be tested in the experiments reported below.

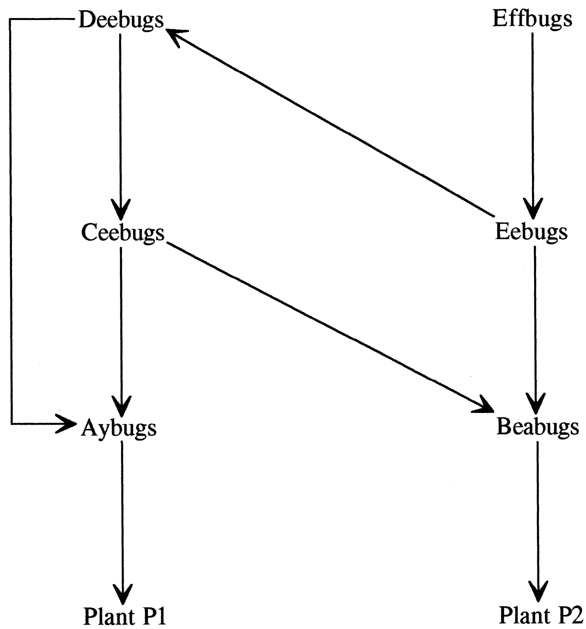

Figure 4. Model food web used by White, (1998, Experiment 1).

2. Multiple Routes. A food web with multiple omnivorous relations was used by White (1998, Experiment 1). Strong support for the dissipation effect was found, but there was also evidence that the existence of multiple routes significantly affected judgments. The food web for this experiment is shown in Figure 4. In this figure the arrows show the direction of the eating relationships: for example, deebugs eat ceebugs and aybugs and are eaten by eebugs. Deebugs and eebugs are omnivores. There are multiple routes between most pairs of locations.

So long as one route to a given location was clearly shorter than others, judgments were not greatly affected by the presence of alternative routes. When there were two equal shortest routes, however, judgments were affected if the unidirectional reasoning implications of those routes were opposite. For example, in one problem participants were informed that the local climate gradually changed in a way that happened to suit plant P1 and not plant P2. Now consider ceebugs. Plant P1 is favored by the climate change and all participants accordingly judged that the population of P1 would increase, by a mean of 76.03 on the 101-point scale. They also judged that aybugs would increase, by a mean of 63.08. Carrying this reasoning through, an increase in ceebugs would seem to be implied because ceebugs eat aybugs. On the other hand, plant P2 is disfavored by the change and all participants judged that the population of P2 would fall, by a mean of 69.87. They also judged that beabugs would decline, by a mean of 66.13. This seems to imply a decrease for ceebugs because they eat beabugs. Thus, two routes from the perturbation to ceebugs are of the same length but have opposite implications. The mean judged change for ceebugs was 4.61, and 32 out of 39 participants judged no change. Substantially greater amounts of

TABLE 3
Terminal v. Nonterminal Species Comparisons

Problem	Number of links distant	Mean	
		Terminal	Nonterminal
White, 1997, problem 2	3	41.74	29.03
White, 1997, problem 3	2	57.39	52.79
White, 1997, problem 3	4	32.96	25.23
White, 1998, expt. 2, problem 1	3	19.92	13.59
White, 1998, expt. 2, problem 1	3	19.92	18.20
White, 1998, expt. 2, problem 2	2	23.91	19.39
White, 1998, expt. 2, problem 2	2	21.96	19.39
White, 1999, expt. 1, problem 1	3	21.58	12.74
White, 1999, expt. 1, problem 2	2	36.89	28.63
White, 1999, expt. 1, problem 2	4	12.53	9.30
White, 1999, expt. 3	3	43.38	43.55
Experiment 1, problem 1	3	48.94	41.54
Experiment 1, problem 1	3	48.69	41.54
Experiment 1, problem 3	2	61.75	55.44
Experiment 1, problem 3	2	62.31	55.44
Experiment 1, problem 4	2	70.87	24.92
Experiment 1, problem 4	2	70.62	24.94

change were judged for other species at the same distance from the perturbation. There is therefore strong evidence that judgments are affected by the presence of multiple routes.

3. Terminal Versus Nonterminal Locations. Holding number of links distant constant, there are 17 possible comparisons between species at terminal locations and species at nonterminal locations in the chosen set of experiments. All 17 are listed in Table 3. In 16 the mean judged change was higher for the terminal location, and there was one minor reversal (less than one scale point difference). This strongly suggests an effect of this factor. The notion that judged change tends to be higher for terminal than for nonterminal locations will be termed the *terminal hypothesis* and will be tested in the experiments reported below.

4. Branching. Assessing the possible effect of branching is not easy. Because of the likely effect of terminal versus nonterminal locations, that factor must be controlled, which greatly reduces the number of possible comparisons. The presence of alternative routes also confounds the assessment of effects of branching in several problems. In the selected problems, therefore, there is only one where relevant factors are well enough controlled that the effect of branching can properly be assessed. This is Problem 4 from White (1997). In this problem two comparisons are possible.

One is for nonterminal species, H1, H2, and H3. The mean judged changes for these three species were, respectively, 67.97, 67.72, and 74.95. One-way analysis of variance with repeated measures was carried out on judgments for these species and a significant effect was found, $F(2,76) = 4.81$, $p < .05$. Post hoc comparisons with the Newman-Keuls test revealed the order H3 > H1 & H2 ($p < .05$ in both cases). This is consistent with the possibility that less change is judged to occur following a branch in the food web.

The other comparison is for terminal species, C1, C2, and C3. C4 could also be included in this comparison, but branching at the terminal level would be confounded with the effect just reported of branching at a nonterminal level, so C4 was omitted from the comparison for this reason. The mean judged changes for the three species were, respectively, 58.10, 58.10, and 63.79. One-way analysis of variance with repeated measures was carried out on judgments for these species and a significant effect was found, $F(2,76) = 7.82$, $p < .01$. Post hoc comparisons with the Newman-Keuls test revealed the order C3 > C1 & C2 ($p < .01$ in both cases). This too is consistent with the possibility that less change is judged to occur following a branch in the food web.

In these comparisons all other relevant factors appear to be controlled: number of links distant from the perturbation, terminal or nonterminal species, the kind of species involved (all herbivores in one case, all carnivores in the other), and there are no alternative routes through the food web. These results therefore lead to the hypothesis that judged change tends to be lower for species following branches than for species not following branches. This will be termed the *branching hypothesis* and will be tested in the experiments reported below.

Summary of Hypotheses and a Possible Explanatory Model

Eight content and structural features of food webs have been examined. In four cases no evidence was found for an effect on judged change. The effects of multiple routes through the food web have been investigated elsewhere (White, 1998, Experiment 1) so this factor will not be further studied in the present research. Evidence suggestive of other kinds of effect has led to the proposal of three novel hypotheses.

The Plant Hypothesis. Greater change is judged to occur for plants than for animals, but only at one link distant from the perturbation.

The Terminal Hypothesis. Judged change tends to be higher for terminal species than for nonterminal species.

The Branching Hypothesis. Judged change tends to be lower for species following branches than for species not following branches.

The main aim of the following experiments is to run predictive tests of these hypotheses using model food webs in which other relevant features are controlled. Of course, it is impossible to be sure that there are really no effects of other structural features: absence of evidence is not evidence of absence. There may be much remaining for future research to discover. But the evidence suggests that the three hypotheses are the best candidates for further investigation, so the present research concentrates on them.

The dissipation effect, the evidence for effects of termini and branching, the lack of evidence for effects of other factors, and the failure of factors such as confidence and content features to explain the observed effects, provide enough clues for a simple explanatory model to be constructed. Under this model the observed effects are outcomes of the possession of a simple physical model of food web dynamics and a way of thinking.

To be specific, the model combines fundamental concepts of influence and resistance with unidirectional reasoning about the operation of influences and resistances in the food web context.

Unidirectional Causal Reasoning. Naive ecology research supports the contention that, beyond a minimal level of system complexity, people engage in unidirectional causal reasoning about food webs (White, 1992a, 1995a, 1997, 1998, 1999; Green, 1997). In other words, when assessing the effects of a perturbation, they trace its route out from the site of the perturbation until they reach a terminus to the food web, and then stop. Assessment of the effects of a perturbation is governed by local considerations only: that is, the judged effect for a given species is affected only by reasoning about parts of the system on the unidirectional route from the perturbation to species X and species posterior to X (unless there are alternative routes of equal length). For example, referring to Figure 1, if the location of the perturbation is P2 and the species being judged is H1, the features of the system that will be considered are the unidirectional route from P2 to H1 through P1, the presence of a branch in the web at P1, and the posterior species C1 and C2. This would explain why, for example, judgment is not significantly affected by species density: species density is a global characteristic of a food web and consequently does not feature in consideration of local features.

Naive Concepts of Influence and Resistance. A food web can be characterized as a trophic structure of functional relationships (Ricklefs, 1993). In other words, a food web is a kind of map of the passage of energy through a physical system. Food is the main source of the energy that a species needs for functions such as reproduction. Other things being equal and excluding possible interactions with factors such as living space, greater availability of food increases the opportunities for a species to multiply. Although ordinary people lack the specialized understanding of professional ecologists, it is not unreasonable to suppose that they possess some informal appreciation of a food web as a structure of energy transfer routes. For example, people probably understand that plants obtain the energy they need for growth and reproduction from sunlight and nutrients in soil. They probably understand that animals obtain the energy they need for growth, survival, and reproduction from what they eat. They probably understand that species, potentially at least, act on population levels of other species by eating them: for example, that foxes eat rabbits and thereby affect their population level, and that squirrels don't. They probably understand that animal and plant species maintain population levels in the face of predation by reproduction, adaptive behaviors, regrowth (in the case of plants such as grass) and so on.

These simple notions are sufficient to permit a general naive conceptualization of food web dynamics in terms of influence and resistance. One species influences another by means of a feeding relationship, and the latter resists that influence by means of reproduction and so forth Under this conceptualization the population level of a species is a function of the relation between influence and resistance. A perturbation to one species is therefore construed as a change in influence, and population levels of other species will be judged as tending to change according to the change in the relation between influence and resistance entailed by the perturbation. The outcome for a given species is determined by the amount of influence from the perturbation that impacts on it and its resistance.[1]

Structural features of food webs affect these factors. Acting to overcome resistance weakens an influence, so the more sources of resistance an influence encounters, the weaker it becomes. The dissipation effect, therefore, is interpreted as progressive reduction in amount of change caused by the progressive weakening of the influence of the perturbation by successive encounters with resisting entities. The influence of the perturbation is also weakened by being divided into two or more channels because whatever goes down one channel cannot go down the other. Thus, less change is judged to occur for species following a branching of the food web because the amount of influence reaching the species is weakened or reduced by the branching. The amount of resistance to change possessed by a species is affected by the presence of species on the far side of it from the perturbation (posterior species). Interactions with these species tend to maintain the population level of the species in question and therefore tend to reduce the impact of the perturbation. Species that have no posterior species lack this source of resistance and are correspondingly more susceptible to the influence of the perturbation. This is the terminal effect.

The basic conception in this model is a kind of contest between influence and resistance. A perturbation is a source of influence affecting the system; species possess a natural resistance to change that opposes the effect of the influence. If this is the kind of conception that people have of food web dynamics, it can be characterized as a naive conception of system properties within a general framework of unidirectional causal reasoning. Instead of complex interactive processes that maintain equilibrium by negative feedback, the natural equilibrium of the system is maintained by the balance between influences and resistances. A change in influence, such as a perturbation, shifts the equilibrium to a different but equally stable state.

This model will be further elaborated in the general discussion. Testing the branching hypothesis and the terminal hypothesis, however, is important to establishing the viability of this proposal about the naive analysis of food web dynamics. This is the aim of the remaining experiments.

IV. EXPERIMENT 2

Method

Participants

The participants were 50 first-year undergraduate students of psychology participating in return for course credit.

Materials

The model food web used in this experiment is shown in Figure 5. All participants received a general information sheet which they retained throughout the experiment. They

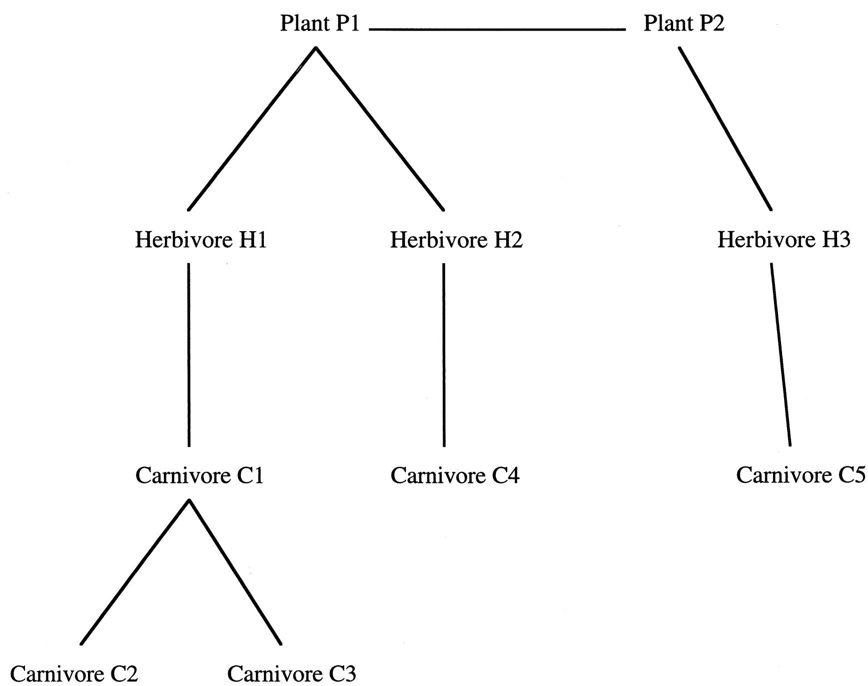

Figure 5. Model food web used in Experiment 2.

were asked to imagine a nature reserve containing various species of plants and animals. All were given the following species information:

Plant P1 thrives best under warm temperatures and low rainfall.
Plant P2 thrives best under cool temperatures and high rainfall.
Plants P1 and P2 compete for space: the more space one has, the less the other has.
Herbivore H1 only eats plant P1.
Carnivore C1 only eats herbivore H1.
Carnivore C2 only eats carnivore C1.
Carnivore C3 only eats carnivore C1.
Herbivore H2 only eats plant P1.
Carnivore C4 only eats herbivore H2.
Herbivore H3 only eats plant P2.
Carnivore C5 only eats herbivore H3.

All participants were also given a copy of Figure 5, which depicts the model food web described by the foregoing information.

Three written problems were presented, always in the same order.

Problem 1: H1 +100%. Participants were asked to imagine that more members of species herbivore H1 are introduced to the reserve, increasing the population of herbivore H1 by 100%—that is, it doubles in size. They were instructed to judge what effect, if any, the increase in size of the population of herbivore H1 would have on the populations of the other species in the reserve. Instructions for judging the likelihood of a *stable* effect were as in Experiment 1.

Participants were asked to indicate "how much change you think will occur by putting a number from –100 to +100 beside the name of each species. For example, if you think that species X will increase by 20%, write "+20" beside it. If you think it will decrease by 20%, write "–20" beside it. If you think that the population of species X will not change, put "0" (zero) beside it. Write down any number from –100 to +100, depending on how much change you think will occur and in which direction." Each of the species other than H1 were listed on the following page and participants recorded their judgments there.

Problem 2: P1 − 50%. Participants were first instructed to forget about the Problem 1 perturbation and imagine that everything was as it had been originally. They were then told to imagine that half of the population of plant P1 is removed from the reserve—that is, the population of plant P1 is halved in size. They were instructed to judge what effect, if any, the decrease in size of the population of plant P1 would have on the populations of the other species in the reserve. The remainder of the instructions were as for Problem 1, and participants made judgments about all species except P1.

Problem 3: Climate Change. Participants were first instructed to forget about the Problem 2 perturbation and imagine that everything was as it had been originally. They were then told to imagine that, as the years pass, global warming takes effect and the local climate of the nature reserve changes somewhat, becoming warmer and drier. They were instructed to judge what effect, if any, this change would have on the populations of the species in the reserve. The remainder of the instructions were as for Problem 1, and participants made judgments about all species.

Hypothesis Testing

The food web was designed to permit several tests of the three hypotheses in a within-participant design.

In Problem 1 the *plant hypothesis* is tested by the comparison between judgments of P1 and C1, both at one link distant from the perturbation, and also by the comparison between P2 and H2, both at two links distant. The prediction is for significantly higher ratings for plants in the former comparison and no significant difference in the latter.

In Problem 2 the *plant hypothesis* is tested by the comparison between P2, H1, and H2, all at one link distant. The prediction is for significantly higher ratings for P2.

In Problem 1 the *terminal hypothesis* is tested by the comparison between C4 and H3, both at three links distant. The prediction is for higher judged change for C4, the terminal species. The hypothesis is also tested by the comparison between C2 and C3, both terminal species, and P2 and H2, all four being at two links distant. The prediction is for higher judged change for C2 and C3.

In Problem 2 the *terminal hypothesis* is tested by the comparison between C4, C1, and H3, all at two links distant. The prediction is for higher judged change for C4, the terminal species.

In Problem 3 the *terminal hypothesis* is tested by the comparison between C1, C4, and C5, all at three links distant. The prediction is for higher judged change for C4 and C5, the terminal species. This comparison also controls for trophic level: the three species are all carnivores predating herbivores in the food web.

In Problem 2 the *branching hypothesis* is tested by the comparison between C2, C3, and C5, all terminal species at three links distant. The prediction is for lower judged change for C2 and C3, the species following a branch.

In Problem 3 the *branching hypothesis* is tested by the comparison between H1, H2, and H3, all nonterminal species at two links distant. The prediction is for lower judged change for H1 and H2, the species following a branch.

Procedure

All details of procedure were as for Experiment 1.

Results

Dissipation Effect

Each problem was analyzed separately. The number of links distant from the perturbation was worked out for each species within each problem using the method described in the introduction and data were analyzed with one-way analysis of variance with repeated measures. In problem 1 (H1 +100) a significant effect was found, $F(3,147) = 39.84$, $p < .001$. Paired comparisons with the Newman-Keuls test revealed the order 1 link $> 2 > 3 > 4$. In problem 2 (P1 − 50) a significant effect was found, $F(2,98) = 17.54$, $p < .001$. Paired comparisons revealed the order 1 link $> 2 > 3$. In problem 3 (climate) a significant effect was found, $F(3,147) = 67.94$, $p < .001$. Paired comparisons revealed the order 1 link $> 2 > 3 > 4$. In all three analyses the results show the usual dissipation effect, and the results can be seen in Figure 6.

Plant Hypothesis

In Problem 1 (H1 + 100) the plant hypothesis was tested with a 2 (number of links, one versus two) × 2 (plant versus animal) analysis of variance with repeated measures. As in tests of the dissipation effect it is the size of the judged change that counts, and the sign is ignored. The main effect of plant versus animal was not significant, $F(1,49) = 2.65$, $p > .1$, and neither was the interaction, $F(1,49) = 0.37$. In fact, there were trends towards higher ratings for animals than for plants, which at one link distant is contrary to the predicted direction of effect. In this analysis, therefore, there was no support for the plant hypothesis.

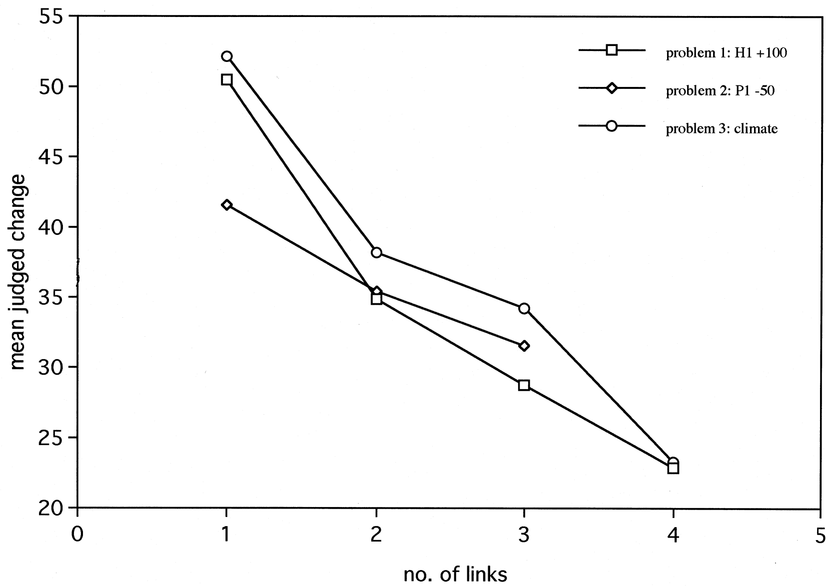

Figure 6. Dissipation effect, Experiment 2.

In Problem 2 (P1 − 50) the plant hypothesis was tested with one-way analysis of variance with repeated measures. The mean judged changes were 50.50 for P2, 37.55 for H1, and 36.95 for H2. The ANOVA produced a significant result, $F(2,49) = 13.84$, $p < .001$, and paired comparisons revealed the order P2 > H1 & H2, $p < .01$ in both cases. This result supports the plant hypothesis.

Terminal Hypothesis

In Problem 1 (H1 + 100) the terminal hypothesis was tested with one-way analysis of variance with repeated measures. The mean judged changes were 32.56 for C4 and 24.96 for H3. The ANOVA yielded a significant result, $F(1,49) = 5.02$, $p < .05$, which supports the terminal hypothesis.

In Problem 2 (P1 − 50) the terminal hypothesis was tested in the same way. The mean judged changes were 32.76 for C4, 33.00 for C1, and 40.50 for H3. The ANOVA produced a significant result, $F(2,49) = 5.14$, $p < .05$. Paired comparisons revealed the order H3 > C1 & C4. This result fails to support the terminal hypothesis and the significant difference between H3 and C4 is opposite to that predicted.

One possible explanation for this lies in the fact that judged change was markedly greater for P2, which lies on the route from the perturbation to H3, than for H1 and H2, which lie on the route from the perturbation to C1 and C4, respectively, as shown in the test of the plant hypothesis reported above. The significant difference between H3 and the other two species might therefore be due to the fact that people judge amount of change for a species not by some absolute standard but by adjusting from the amount of change judged for the previous species on the route. This is testable: if the terminal hypothesis is correct, the amount of adjustment should be less for a terminal than for a nonterminal species. A difference measure can be constructed by subtracting a participant's judgment for a species from their judgment for the previous species on the route. Thus, the judgment for H3 is subtracted from that for P2, that for C4 from that for H2, and that for C1 from that for H1. The mean difference scores resulting from this procedure were 4.19 for C4, 4.55 for C1, and 10.00 for H3. Analysis of variance on the difference scores produced a significant result, $F(2,49) = 4.98$, $p < .05$. Paired comparisons revealed the order C4 & C1 > H3. The significant difference between C4 and H3 supports the foregoing reasoning and means that the results are not inconsistent with the terminal hypothesis. However, there was no significant difference between C4 and C1 on either measure, contrary to prediction. This does not support the terminal hypothesis. A possible interpretation will be considered in the discussion.

In Problem 3 (climate) the terminal hypothesis was tested with one-way analysis of variance with repeated measures. The mean judged changes were 41.69 for C5, 29.36 for C4, and 31.76 for C1. The ANOVA produced a significant result, $F(2,49) = 20.65$, $p < .001$. Paired comparisons revealed the order C5 > C1 & C4. The result for the comparison between C5 and C1 supports the terminal hypothesis, but that for the comparison between C4 and C1 does not. This is the same comparison as the one that failed in problem 2, and the same interpretation, to be discussed below, could apply.

Branching Hypothesis

In Problem 2 (P1 − 50) the branching hypothesis was tested with one-way analysis of variance with repeated measures. The mean judged changes were 35.35 for C5, 29.24 for C2, and 29.50 for C3. Analysis yielded a significant result, $F(2,49) = 3.23$, $p < .05$. Paired comparisons revealed no significant differences, but the combination of the positive prediction and the significant F ratio justifies analysis of selected contrast among means, comparing C5 with C2 and C3. By this analysis C5 was significantly different from the combination of C2 and C3, $F(1,49) = 7.97$, $p < .01$. This supports the branching hypothesis for terminal species.

Under the terminal hypothesis, however, it was argued that participants might be judging the amount of change for a given species by adjusting from the amount judged for the previous species en route, and a difference score measure was used to test this possibility. The same reasoning could apply here and for the same reason: these species are all one stop further down the line from those included in the difference score analysis above. Therefore the same procedure was applied here and the mean difference scores were 5.26 for C5, 3.73 for C2, and 3.46 for C3. Analysis of variance on these data revealed no significant effect, $F(2,49) = 0.42$. It is therefore possible that the difference between C5 and the other two in the main analysis can be accounted for by the idea that participants are adjusting from previous judgments.

In Problem 3 (climate) the branching hypothesis was tested with one-way analysis of variance with repeated measures. The mean judged changes were 45.00 for H3, 35.16 for

H1, and 34.46 for H2. Analysis yielded a significant result, $F(2,49) = 19.04$, $p < .001$. Paired comparisons revealed the order H3 > H1 & H2, which supports the branching hypothesis for nonterminal species. In this case the adjustment hypothesis considered in the previous paragraph cannot explain the results because the means for the relevant previous species, P1 and P2, were almost identical, differing by less than one point on the 101-point scale. To make sure, difference scores were assessed as before. The means were 7.40 for H3, 16.74 for H1, and 17.44 for H2. Analysis revealed a significant effect, $F(2,49) = 20.47$, $p < .001$, and paired comparisons revealed the same differences as before. This supports the branching hypothesis.

Discussion

The dissipation effect appeared in all three problems. One analysis supported the plant hypothesis but another failed to do so, and indeed the direction of difference in the means was against the hypothesis. Both tests of the branching hypothesis yielded supportive evidence, but there is an alternative possible explanation for one of the results. Two tests of the terminal hypothesis yielded supportive evidence and the analysis of difference scores in the third test also did so, but two comparisons failed to support the hypothesis. These both involved comparisons between C1 and C4, two links distant from the perturbation in Problem 2 and three links distant in Problem 3.

One possible explanation for these two failures is visible in Figure 5. The structure of the food web between the perturbation and the two species in question is clearly symmetrical about a vertical line, dividing at plant P1 and each branch then passing through one herbivore without further branching. C1 and C4 sit beside each other in the figure, so the symmetrical nature of that part of the structure is readily apparent. One possible explanation for the results, therefore, is that participants detected this symmetrical arrangement and it functioned as an implicit demand for similar judgments to be made about the two species. Under one possible interpretation, the structure might have cued the participants to the kind of response they thought the experimenter expected (Orne, 1962; Adair & Spinner, 1981); under another they might have experienced evaluation apprehension (Rosenberg, 1965) and were afraid of being negatively evaluated by the experimenter if they gave different judgments to the two species. In support of this, 43 out of 50 participants (86%) gave the same judgment of change to C1 and C4 in Problem 2 and 39 out of 50 (78%) on Problem 3, which on a 101-point scale is very unlikely to be a chance occurrence.

There are therefore several priorities for the remaining experiments: to run further tests of the plant hypothesis in the hope of shedding more light on the mixed results obtained so far; to test the branching hypothesis for nonterminal species with the aim of ruling out the alternative interpretation in terms of adjustment; and to test the hypothesis that participants make similar judgments for species that are adjacent in clearly symmetrical postperturbation structures. Experiment 3 concentrates on the first two of these.

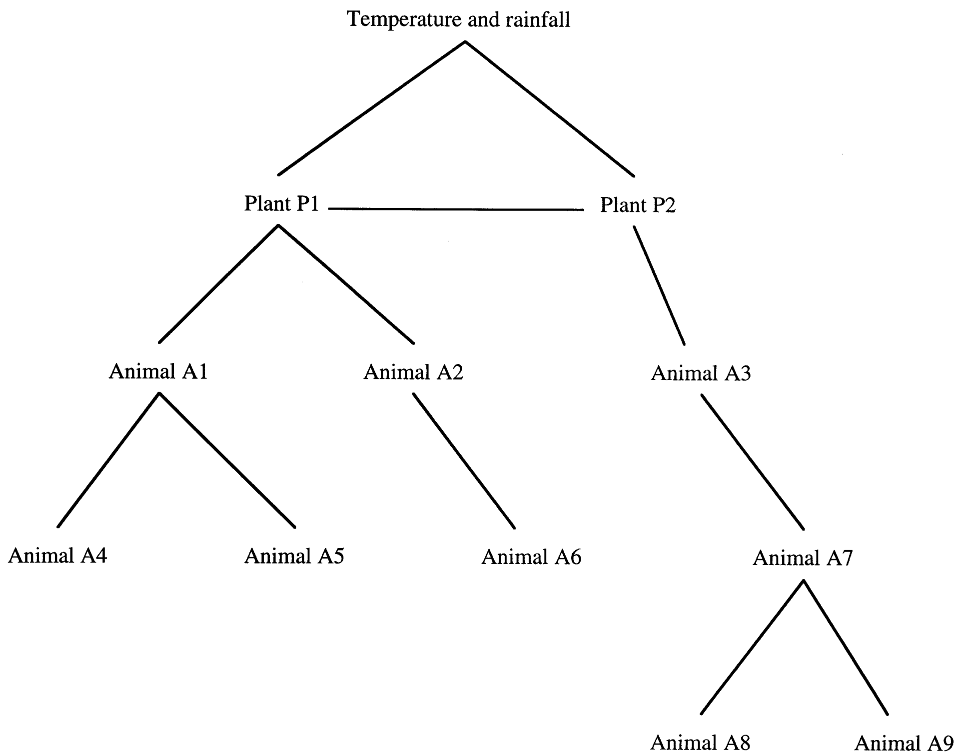

Figure 7. Model food web used in Experiment 3.

V. EXPERIMENT 3

Method

Participants

The participants were 40 first-year undergraduate students of psychology participating in return for course credit.

Materials

The model food web used in this experiment is shown in Figure 7. All participants received a general information sheet, which they retained throughout the experiment. They were asked to imagine a nature reserve containing various species of plants and animals. All were given the following species information:

Plant P1 thrives best under warm temperatures and low rainfall.

Plant P2 thrives best under cool temperatures and high rainfall.

Plants P1 and P2 compete for space: the more space one has, the less the other has.

Animal A1 only eats plant P1.

Animal A2 only eats plant P1.
Animal A3 only eats plant P2.
Animal A4 only eats animal A1.
Animal A5 only eats animal A1.
Animal A6 only eats animal A2.
Animal A7 only eats animal A3.
Animal A8 only eats animal A7.
Animal A9 only eats animal A7.

All participants were also given a copy of Figure 7, which depicts the model food web described by the foregoing information.

Two written problems were presented, always in the same order.

Problem 1: A3 + 100%. Participants were asked to imagine that more members of species animal A3 are introduced to the reserve, increasing the population of animal A3 by 100%—that is, it doubles in size. They were instructed to judge what effect, if any, the increase in size of the population of animal A3 would have on the populations of the other species in the reserve. Instructions for judging the likelihood of a *stable* effect were as in Experiment 1. Instructions for the change judgment were as in Experiment 2. Participants made judgments of change for all species except A3.

Problem 2: P2 − 50%. Participants were first instructed to forget about the Problem 1 perturbation and imagine that everything was as it had been originally. They were then told to imagine that half of the population of plant P2 is removed from the reserve—that is, the population of plant P2 is halved in size. They were instructed to judge what effect, if any, the decrease in size of the population of plant P2 would have on the populations of the other species in the reserve. The remainder of the instructions were as for Problem 1, and participants made judgments about all species except P2.

Hypothesis Testing

In Problem 1 the *plant hypothesis* is tested by the comparison between judgments of P2 and A7, both at one link distant from the perturbation. The prediction is for significantly higher ratings for P2. The comparison between P1, A8, and A9 at two links distant cannot be included in this test because the latter two are terminal species and also follow a branch in the web, whereas neither of these things is the case for P1.

In Problem 2 the *plant hypothesis* is tested by the comparison between judgments of P1 and A3, both at one link distant from the perturbation. The prediction is for significantly higher ratings for P1.

In Problem 1 the *branching hypothesis* for terminal species is tested by the comparison between A4, A5, and A6, all terminal species at four links distant. The prediction is for lower judged change for A4 and A5, the species following a branch.

In Problem 2 the *branching hypothesis* for terminal species is also tested by the comparison between A4, A5, and A6, all terminal species this time at three links distant. The prediction is for lower judged change for A4 and A5, the species following a branch.

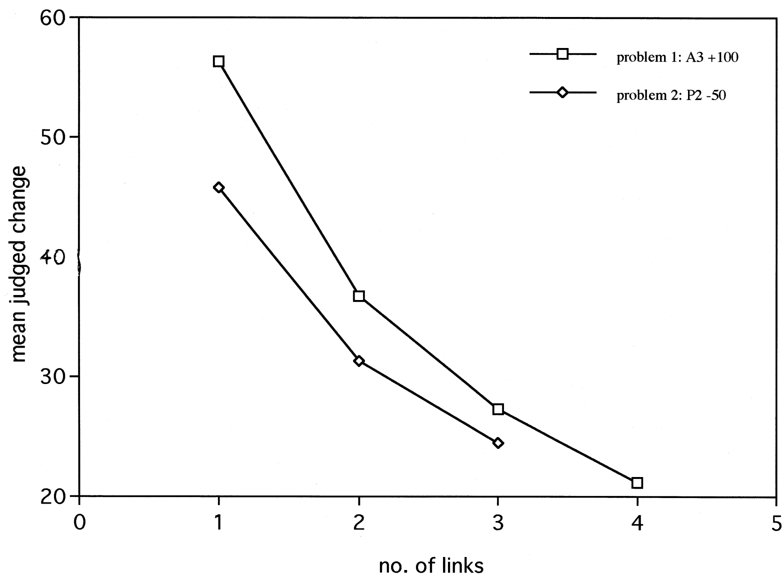

Figure 8. Dissipation effect, Experiment 3.

A8 and A9, also terminal species at three links distant, cannot be included in this comparison because there is a branch in the web on the route from P2 to A4, A5, and A6 (after P1), but no branch on the route from P2 to A8 and A9, except at A8 and A9 themselves.

In Problem 2 the *branching hypothesis* for nonterminal species is tested by the comparison between A1, A2, and A7, all nonterminal species at two links distant. The prediction is for lower judged change for A1 and A2, the species following a branch.

Procedure

All details of procedure were as for Experiment 1.

Results

Dissipation Effect

Each problem was analyzed separately. The number of links distant from the perturbation was worked out for each species within each problem using the method described in the introduction and data were analyzed with one-way analysis of variance with repeated measures. In Problem 1 (A3 + 100) a significant effect was found, $F(3,117) = 63.49$, $p < .001$. Paired comparisons revealed the order 1 link > 2 > 3 > 4. In problem 2 (P2 − 50) a significant effect was found, $F(2,78) = 69.98$, $p < .001$. Paired comparisons revealed the order 1 link > 2 > 3. In both analyses the results show the usual dissipation effect, and the results can be seen in Figure 8.

Plant Hypothesis

In Problem 1 (A3 + 100) the plant hypothesis was tested with one-way analysis of variance with repeated measures on the comparison between P2 and A7. The mean judged changes were 60.50 for P2 and 52.12 for H2. Although this difference is in the predicted direction it fell short of statistical significance, $F(1,39) = 3.09$, $p = .09$.

In Problem 2 (P2 − 50) the plant hypothesis was tested with one-way analysis of variance with repeated measures on the comparison between P1 and A3. The mean judged changes were 46.25 for P2 and 45.37 for H2. The analysis showed that this difference was not statistically significant, $F(1,39) = 0.05$.

Branching Hypothesis

In Problem 1 (A3 + 100) the branching hypothesis for terminal species was tested with one-way analysis of variance with repeated measures on the comparison between A4, A5, and A6. The mean judged changes were 20.11 for A4, 19.79 for A5, and 23.57 for A6. Analysis yielded a significant result, $F(2,78) = 10.19$, $p < .001$. Paired comparisons revealed the order A6 > A4 & A5, $p < .01$ in both cases. This supports the branching hypothesis. In this case the adjustment hypothesis considered in Experiment 2 cannot explain the results because the means for the relevant previous species, A1 and A2, were almost identical, differing by less than one point on the 101-point scale.

In Problem 1 the branching hypothesis for terminal species was tested with one-way analysis of variance with repeated measures on the comparison between A4, A5, and A6. The mean judged changes were 17.11 for A4, 17.09 for A5, and 20.06 for A6. Analysis yielded a significant result, $F(2,78) = 6.39$, $p < .01$. Paired comparisons revealed the order A6 > A4 & A5, $p < .01$ in both cases. This supports the branching hypothesis. Here too the adjustment hypothesis considered in Experiment 2 cannot explain the results because the means for the relevant previous species, A1 and A2, differed by less than one point on the 101-point scale.

In Problem 2 (P2 − 50) the branching hypothesis for nonterminal species was tested with one-way analysis of variance with repeated measures on the comparison between A1, A2, and A7. The mean judged changes were 29.10 for A1, 28.35 for A2, and 36.55 for A7. Analysis yielded a significant result, $F(2,78) = 4.58$, $p < .05$. Paired comparisons revealed the order A7 > A1 & A2, $p < .05$ in both cases. This supports the branching hypothesis. Here too the adjustment hypothesis considered in Experiment 2 cannot explain the results because the means for the relevant previous species, P1 and A3, differed by less than one point on the 101-point scale.

Discussion

In this experiment three tests of the branching hypothesis all provided a significant degree of support: in each case the mean judged change was lower for species following a branching of the web than for species at the same number of links distant from the perturbation but not following a branch. Moreover in each case the possibility that the difference might have been due to adjusting from means for previous species was ruled out because the means for the previous species were virtually identical.

The results gave little support to the plant hypothesis, however, and this hypothesis must be regarded as dubious, at best. There is no obvious reason why judged change should be greater for plants than for animals only at one link distant. Although one of the tests of the hypothesis in Experiment 2 gave strong support, it is possible that there is some other explanation for the difference observed there, and other tests have largely failed to support the hypothesis. It will not be further investigated.

VI. EXPERIMENT 4

In the discussion of Experiment 2, it was suggested that some comparisons failed to yield statistically significant differences because participants were responding to an obviously symmetrical structure in the food web between the perturbation and the species being judged, treating it as a cue to make similar judgments about species at equivalent locations in the symmetrical structure. The main aim of Experiment 4 is to test this possibility, using a model food web with evident symmetry. The salience of symmetry is enhanced by the use of a simple food web with few locations. It is difficult to set up a test of the terminal hypothesis without introducing unwelcome complexity into the food web, so instead the branching hypothesis will be tested. An additional feature of the experiment is that the branching hypothesis will be tested in a between-participant design instead of the within-participant designs that have been used hitherto.

Method

Participants

The participants were 56 first-year undergraduate students of psychology participating in return for course credit.

Materials

The model food webs used in this experiment are shown in Figures 9 and 10. Figure 9 shows the food web used in the *complex web* condition and Figure 10 shows the food web used in the *simple web* condition. The difference between the two webs is the appearance in the complex web of two extra predators of animal A2, A5 and A6.

All participants received a general information sheet, which they retained throughout the experiment. They were asked to imagine a nature reserve containing various species of plants and animals. Participants in the complex web condition were given the following species information:

There is just one species of plant in the reserve, P1.

Animal A1 only eats plant P1.

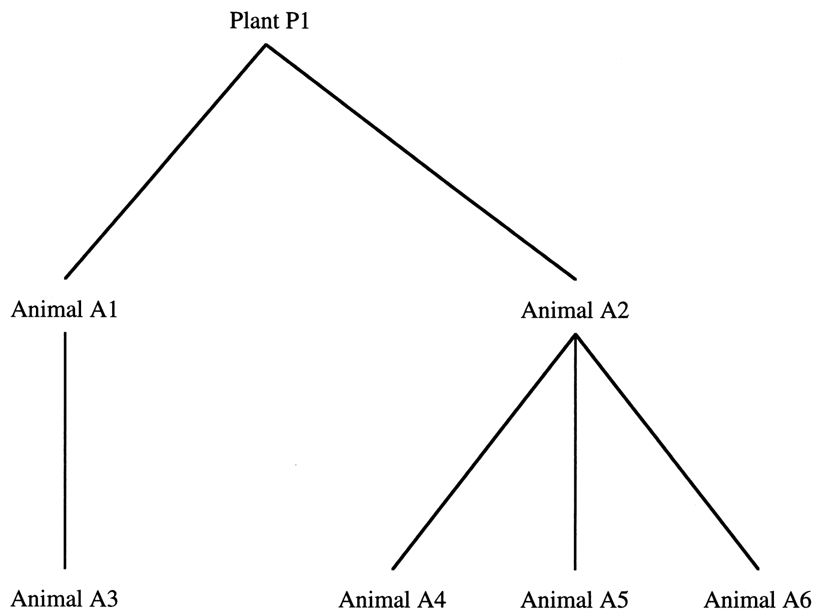

Figure 9. Complex web, Experiment 4.

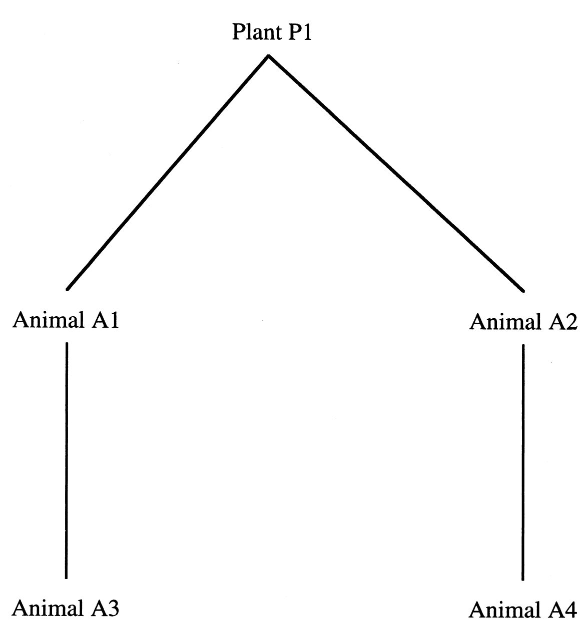

Figure 10. Simple web, Experiment 4.

Animal A2 only eats plant P1.
Animal A3 only eats animal A1.
Animal A4 only eats animal A2.
Animal A5 only eats animal A2.
Animal A6 only eats animal A2.

They were also given a copy of Figure 9. Participants in the simple web condition were given the same information except that the information about A5 and A6 was absent. They also received a copy of Figure 10.

Two written problems were presented, always in the same order.

Problem 1: P1 − 50%. Participants were asked to imagine that plant P1 undergoes a rapid natural decline to half its former level—in other words, the population of plant P1 decreases by 50%. They were instructed to judge what effect, if any, the 50% decrease in the population of plant P1 would have on the populations of the other species in the area. Instructions for judging the likelihood of a *stable* effect were as in Experiment 1. Instructions for the change judgment were as in Experiment 2. Participants made judgments of change for all species except P1.

Problem 2: A1 + 100%. Participants were first instructed to forget about the Problem 1 perturbation and imagine that everything was as it had been originally. They were then told to imagine that more members of species A1 migrate into the area, doubling the population of animal A1—in other words, the population of animal A1 increases by 100%. They were instructed to judge what effect, if any, the 100% increase in the population of animal A1 would have on the populations of the other species in the area. The remainder of the instructions were as for problem 1, and participants made judgments about all species except A1.

Tests of Hypotheses

The species of primary interest in this experiment is A4. The addition of A5 and A6 in the complex web condition makes the comparison between A4 in the simple and complex conditions a test of the branching hypothesis, and, under that hypothesis, lower judgments would be expected for A4 in the complex web condition in both problems. In Problem 1, however, the perturbation is to plant P1, and the structure of the food web between the perturbation and species A4 and A3 is clearly symmetrical about a vertical line, just as the structure between the perturbation and C1 and C4 was in Experiment 2. In Problem 2 the perturbation is to A1, which means that A3 and A4 are at different distances from the perturbation (one link and three, respectively). In this problem the structure between the perturbation and these two species is not symmetrical, and they are in any case unlikely to be compared because of being at different distances from the perturbation. Under this reasoning, therefore, it is expected that support for the branching hypothesis will be found in Problem 2, but that in Problem 1 the effect of symmetry will override that of branching.

This can be tested by comparing judgments of A4 in Problem 1 and Problem 2. The expectation is that there should be no difference between the simple and complex web conditions in Problem 1, but that judgments of A4 should be lower in the complex than in the simple web condition in Problem 2. Comparison between judgments of A4 and A3 might be thought desirable, but is only valid within Problem 1 because in Problem 2 A3 and A4 are at different distances from the perturbation. It would be expected, however, that differences between judgments in the complex and simple conditions would occur only for A4 and not for the other species, and this test will also be carried out.

Procedure

All details of procedure were as for Experiment 1.

Results

Dissipation Effect

Each problem was analyzed separately. The number of links distant from the perturbation was worked out for each species within each problem using the method described in the introduction and data were analyzed with two-way mixed design analysis of variance with one between-participant measure (complex versus simple web) and one within-participant measure (number of links distant).

In Problem 1 (P1 − 50) just one significant result was found, a main effect of number of links distant, $F(1,54) = 13.69$, $p < .001$, with higher judged change for species at one link distant than for species at two links distant. There was no effect of or interaction with web condition ($F < 1$ in both cases).

In Problem 2 (A1 + 100) there was a significant main effect of number of links distant, $F(2,108) = 23.66$, $p < .001$. Paired comparisons revealed the order 1 link > 2 > 3 ($p < .01$ in all cases). The main effect of complex v. simple web was not significant ($F < 1$), but there was a significant interaction, $F(2,108) = 5.18$, $p < .01$. This is due to the predicted effect of branching and will be examined with the planned analyses below. The dissipation effect in both problems can be seen in Figure 11.

Tests of Hypotheses

The symmetry and branching hypotheses were tested with a 2 between (complex versus simple web) × 2 within (problem 1 versus problem 2) mixed design analysis of variance on judged change for animal A4. There was a significant main effect of problem, $F(1,54) = 27.66$, $p < .001$. This is the dissipation effect, because A4 lies at two links distant from the perturbation in Problem 1 and three in Problem 2. The main effect of web was not significant, $F(1,54) = 1.95$, $p > .1$. The interaction between the two variables was marginally significant, $F(1,54) = 3.28$, $p = .08$. Simple effects analyses revealed no significant difference between the complex and simple conditions in Problem 1, $F(1,54) = 0.11$. There was, however, a significant difference between the complex and simple conditions in Problem 2, $F(1,54) = 4.37$, $p < .05$. These results are as predicted. The

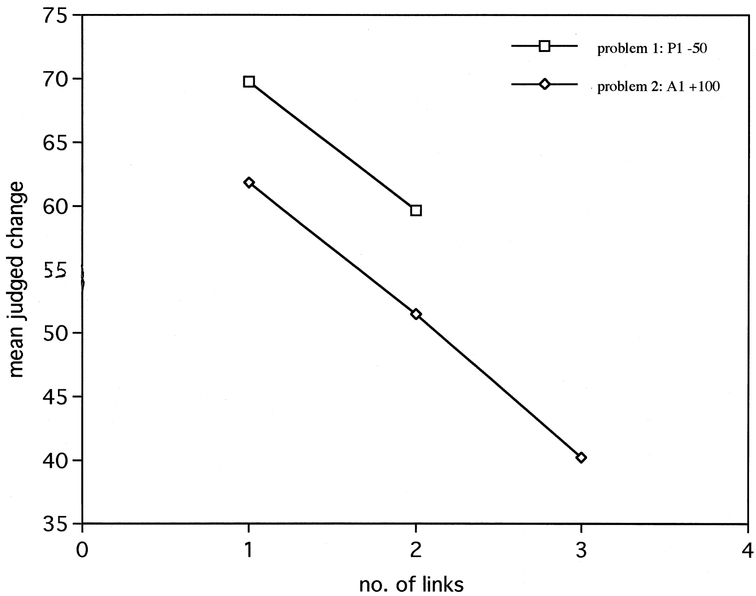

Figure 11. Dissipation effect, Experiment 4.

significant difference on Problem 2 supports the branching hypothesis, and the failure to find a difference on Problem 1 is consistent with the symmetry hypothesis. Means are presented in Table 4.

Within Problem 1 (P1 − 50), judgments of change for species A3 and A4 were compared in a 2 between (complex versus simple web) × 2 within (A3 versus A4) mixed design analysis of variance. No significant effects were found ($F < 1$ in every case). This is consistent with the symmetry hypothesis, though of course the usual cautions about nonsignificant results apply.

Within Problem 2 (A1 + 100), judgments of change were compared in a 2 between (complex versus simple web) × 4 within (species, P1 versus A 2 versus A3 versus A4) mixed design analysis of variance. A significant main effect of species was found, $F(3,162) = 14.92$, $p < .001$, which is again the dissipation effect. The main effect of web was not significant, $F(1,54) = 0.25$. There was a significant interaction, $F(3,162) = 2.85$, $p < .05$. Simple effects analysis revealed the significant effect for A4 already described.

TABLE 4
Mean Judged Change for Animal A4, Experiment 4

Web condition	Problem 1	Problem 2	Both
Complex	58.61	32.25	45.43
Simple	61.07	48.21	54.64
Both	59.84	40.23	

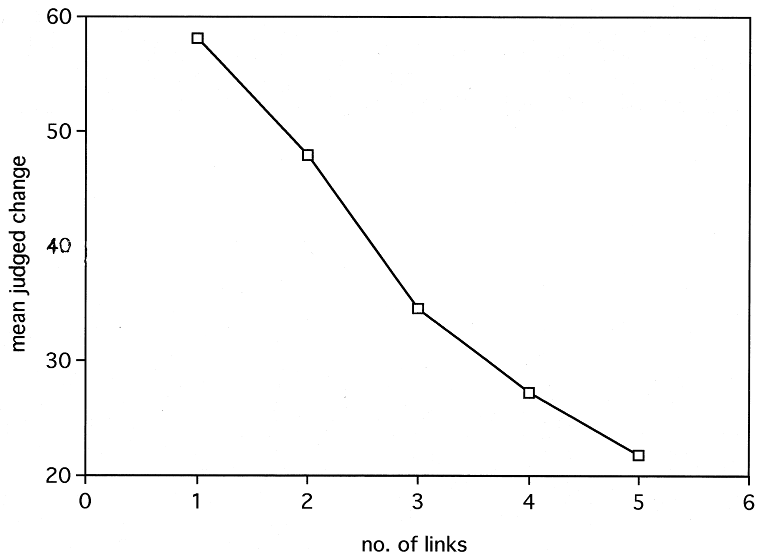

Figure 12. Dissipation effect, means of means in 27 problems.

There was no significant difference between the complex and simple web conditions for any other species ($F < 1$ in all cases).

To summarize, the results were consistent with the hypotheses. In Problem 2 support for the branching effect was found, and there were no significant differences between the complex and simple web conditions other than the predicted effect. In Problem 1 no differences were found between the complex and simple web conditions or between A3 and A4, consistent with the reasoning about the evident symmetry in the web. Evident symmetry therefore appears to be a major methodological obstacle to the testing of hypotheses about the naive understanding of food webs, and the problems it poses must be borne in mind in any future experiments.

VII. GENERAL DISCUSSION

In all four experiments strong support was found for the dissipation effect. There have now been 27 tests of the dissipation effect: four tests in White (1997), three in White (1998, Experiment 1), two in White (1998, Experiment 2), four in White (1998, Experiment 3), two in White (1999, Experiment 1), one in White (1999, Experiment 3), four in Experiment 1 above, three in Experiment 2 above, two in Experiment 3 above, and two in Experiment 4 above. All of these have used the same 101-point rating scale so the mean for each number of links distant can be calculated for all 27 problems. The resultant overall means are plotted in Figure 12.

The number of means entering this calculation tends to decrease with increasing numbers of links because in some problems there were no species at larger numbers of

TABLE 5
Mean Judged Change for Each Kind of Perturbation

Kind of perturbation	Number of links distant 1	2	3	4
Species introduction (n = 4)	58.93	43.26	29.05	23.66
Species increase (n = 5)	55.23	40.30	30.49	27.33
Species decrease (n = 5)	51.83	43.48	30.91	13.20*
Species elimination (n = 4)	53.90	44.05	26.46	21.94
Climate change (n = 3)	70.10	57.67	38.76	21.32
Toxicity introduction (n = 1)	64.19	55.45	24.31	—

*n = 1.

links distant. Despite this, the overall trend is clear. There is now sufficient evidence to regard the dissipation effect as established.[2]

Research has ruled out a number of possible explanations for the dissipation effect. White (1998, Experiment 2) found that the effect could not be accounted for by changes in participants' confidence in their ratings of different species. White (1999, Experiment 1) found that the effect was not significantly affected by presence or absence of a diagram of the food web nor by whether participants were asked to judge change after one year or ten years. White (1999, Experiment 2) found that the effect was not associated with the length of the causal chain participants were asked to judge but was associated with the structure of the food web. Two experiments have found that people judge dissipation to be a lasting and stable pattern of population change following a perturbation (White, 1999, Experiments 1 and 3).

In addition, reconsideration of evidence from previous studies has found that a number of content and structural factors have no significant effect on judgments of population change. These include whether the direction of judged change is an increase or a decrease, whether or not the route from perturbation to species being judged involves a change of direction in the food web, how many species follow the species being judged in terms of unidirectional routes through the web, and how many species there are within a given distance of the perturbation. Whether the kind of thing being judged is a plant or an animal may make a difference at a distance of one link from the perturbation, but the evidence is inconclusive.

Adding the four experiments reported above to those in previous studies permits one further factor to be considered: the kind of perturbation in the problem. Table 5 lists the kinds of perturbation used in the experiments (not including White, 1998, Experiment 3) and the mean judged change for each type. There is suggestive evidence that greater amounts of change are judged in climate change problems, or perhaps that the slope of judged change across numbers of links distant is steeper, but the dissipation effect is remarkably uniform across kinds of perturbation. There is therefore no evidence for an effect of kinds of perturbation.

There is evidence, however, that three factors additional to number of links distant from the perturbation make a difference to judgments of population change. One of these,

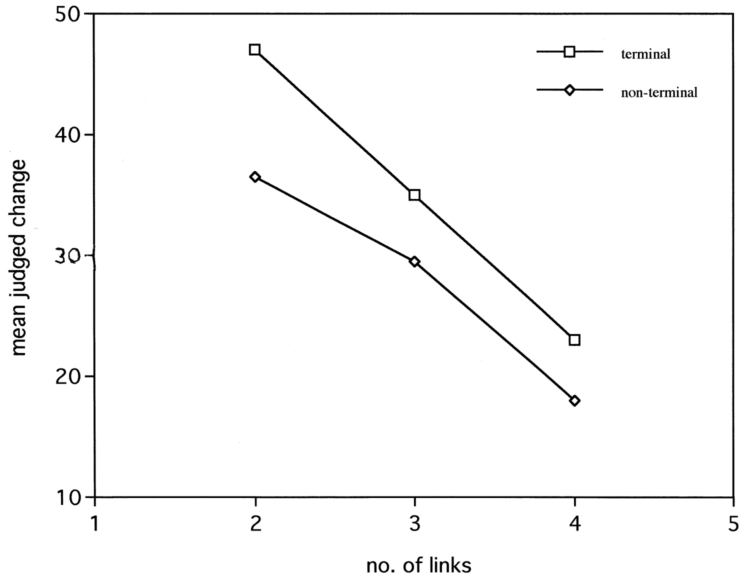

Figure 13. Terminal effect, overall means.

investigated by White (1998, Experiment 1) is the presence of multiple routes of equal length from the perturbation to the species in question. The present experiments have also found evidence for effects of two other factors.

One, the branching effect, is a tendency for judged change to be lower for species following a branch in the food web than for species not following a branch. Signs of this tendency were found in the reconsideration of the previous experiments, and support for it was found both for species at terminal locations and for species at nonterminal locations in Experiments 2, 3, and 4.

The other, the terminal effect, is a tendency towards higher judgments of change for species at terminal locations in the food web than for species at nonterminal locations the same number of links distant from the perturbation. This effect is summarized in Figure 13, which shows means of all the means in Table 3 and the tests of the hypothesis in Experiment 2 above. The figure presents means separately for two, three, and four links distant from the perturbation. The tendency in support of the terminal effect is strong and consistent overall, as shown by the fact that the lines in Figure 13 are close to parallel.

Influence and Resistance Model

The evidence of these experiments therefore supports the explanatory model sketched out earlier. Under this model people make causal judgments by applying naive conceptions of influence and resistance in a process of unidirectional causal reasoning. A perturbation is conceived as a change that acts to influence properties of the system, in this case population levels. The structure of the food web is essentially a map of channels for the transmission of influence through the system. Locations in the system possess resistance to change.

The central proposition in the model is that the judged change to the population of a given species following a perturbation is a function of the amount of influence reaching that location in the system and the amount of resistance possessed by that location. More influence implies greater judged change. More resistance implies less judged change. The amount of influence acting on a given species is determined by the number of links in the web between the perturbation and the species, and by the number of branching connections on the route from the perturbation to the species. The greater the number of links, and the greater the number of branches, the less influence acts on the species. The amount of resistance possessed by the species is the sum of two quantities: the intrinsic resistance of that species and the extrinsic resistance conferred on the species by the bolstering effect of species on the far side of it from the perturbation.

Those propositions encompass all the effects reported here. The dissipation effect is due to the weakening of the influence of the perturbation caused by successive encounters with resisting entities. The terminal effect is due to the fact that terminal species possess only intrinsic resistance, whereas nonterminal species possess both intrinsic and extrinsic resistance. The branching effect is due to the weakening of the influence of the perturbation caused by division of the channels of energy transfer: if the route divides, the amount of influence divides as well.

The model can also explain the effects of multiple routes observed in White (1998, Experiment 1). In that research, where there were two routes of differing lengths between a perturbation and a given species, participants' judgments tended to be dominated by the unidirectional reasoning implications of the shorter route. Under the influence and resistance model, the explanation for this is that the influence of the perturbation has diminished less along the shorter route than along the longer route. More influence implies greater judged change, so the influence along the shorter route has a greater effect on the species than the influence along the longer route. Where there are two routes of equal length and with opposite unidirectional reasoning implications for the species, however, the influence of the perturbation is roughly equal along both routes (other things, such as branches, being equal), and so the two implications effectively cancel out, leading to judgment of no change. This is the pattern found by White (1998, Experiment 1).

There is a good deal of evidence from naive ecology research that people engage in unidirectional causal reasoning about food web dynamics beyond a certain minimal level of system complexity, which appears to be roughly two species (White, 1992a, 1995a, 1997, 1998; Green, 1997). In the naive model of food web dynamics proposed here, the effects of perturbations are judged by unidirectional reasoning: in other words, people follow the route of the perturbation out from its location to the termini of the food web, and do not consider complex interactions or simple feedback. However, if the interpretation of the terminal effect proposed here is correct, then people do have and employ a simple conception of interactional effects in complex physical systems: the amount of change judged to occur at a given location is the result of a contest between the influence of the perturbation, tending to produce change, and the resistance to change at that location, tending to maintain the previous population level.

Comparison with Expert Analysis

This contrasts with expert analyses of food web dynamics (Pimm, 1982; Ricklefs, 1993). Food webs, as was noted in the introduction, tend to be stable, and equilibrium levels of population tend to be maintained and restored by processes of negative feedback operating through the interspecies connections that define the structure of the food web. The complexity of these structures means that predicting the effects of perturbations is very difficult and that they can be ascertained only by experiment (Ricklefs, 1993). Although the short-term effects of perturbations tend to be cancelled out by processes that restore the previous equilibrium, stability does depend on some global features of food webs.

One of these is omnivory. An omnivore is a species that feeds on more than one trophic level. Figure 4 shows a food web with a high degree of omnivory. For example, deebugs are omnivores, feeding on both ceebugs and deebugs, which occupy different trophic levels. So are eebugs. Figure 1, on the other hand, shows a food web with no omnivores. Increasing omnivory tends to reduce the stability of a food web (Ricklefs, 1993). By that criterion an expert would judge the food web in Figure 1 (and those in Figures 5, 7, 9, and 10) to be comparatively stable, meaning that a perturbation would be relatively likely to be followed by restoration of the preceding equilibrium.

However, food webs that are dominated by a single predator can be less stable. Experimental studies have shown that removal of such predators from the community, in effect releasing other species from predation, can lead to drastic changes, such as explosive proliferation of one species at the expense of others (Ricklefs, 1993). Such predators are called keystone predators because their removal brings about the collapse of the food web. Problems used in the present studies avoided perturbations involving the complete removal of a predator: although this was done in Problem 3 of Experiment 1 (A5 $-$ 100), it is unlikely that A5 would be a keystone predator because the species predated by it, A1, is also predated by A4 (see Figure 2), and is therefore not released from predation by the removal of A5.

Thus, although the influence and resistance model could be described as a kind of two-way causal thinking, a conceptualization of interactions in terms of the contest between influence and resistance, it is simpler and different in character from the kind of two-way causal thinking that characterizes expert reasoning about food webs. In expert reasoning each species is affected by interactions involving the whole of the rest of the food web in processes of negative feedback. Dissipation, the branching effect, and the terminal effect do not naturally emerge from that kind of reasoning, and have not been found to occur in experimental studies. Restoration of previous equilibria or radical change with the eventual establishment of new equilibrium levels unpredictably different from the old ones are the usual alternatives, depending on the structure of the food web and the nature of the perturbation.

With the food webs used here, theoretical analyses and experimental work would suggest that restoration of the previous equilibria is the most likely outcome, though predictions cannot be made with any confidence. Nonetheless, it is a striking feature of research on the dissipation effect that people *never* judge that the previous equilibrium will be restored: even for species furthest from the perturbation, the proportion of participants judging zero change rarely exceeds 20%, and is usually much less (see footnote 3 for illustrative data). Zero change seems like the simplest option, the default option, so the fact that it rarely occurs in judgments strongly suggests that those judgments reflect the application of a positive theory or reasoning tendency.

Ohm's p-prim

The basic concepts in the model are those of influence and resistance. These closely resemble the components of a model called "Ohm's p-prim" (diSessa, 1983, 1993). Phenomenological primitives, or p-prims, are primitive notions that stand "without significant explanatory substructure or justification" (diSessa, 1983, p.15) and lie at the root of many explanations and justifications. diSessa proposed that Ohm's p-prim comprises four subentities: "an *agent* that is the locus of an *impetus* that acts against a *resistance* to produce some sort of *result*" (diSessa, 1993, p.126). This simple scheme supports a variety of qualitative propositions, such as that "more effort implies more result; more resistance implies less result; and so on" (diSessa, 1993, p.126). diSessa argued that Ohm's p-prim is the foundation of interpretations of phenomena in many contexts. He cited as examples "pushing harder in order to make objects move faster,. . . modeling interpersonal relations such as a parent's offering more and more encouragement to counter a child's offering increasing resistance" (1983, p. 25), predicting the change in pitch of sound produced by a vacuum cleaner when the nozzle is obstructed, and current flow in an electrical circuit (see also Gentner & Gentner, 1983).

The phenomena of the naive analysis of food webs can be explained as an application of this fundamental and possibly primitive domain-general set of concepts to the food web domain. The explanation proposed for the dissipation effect, therefore, is that it is the outcome of the application to a complex physical system of a phenomenologically primitive set of concepts about force and resistance. This interpretation implies that dissipation should be a general phenomenon of judgments about complex physical systems, provided only that concepts of influence and resistance are judged applicable to the system in question. Support for this comes from White (1998, Experiment 3). The stimulus materials in this experiment presented information about a hypothetical lake, and the causal relations that pertained between variables such as evaporation, humidity, temperature, cloud, wind, and rain. In four problems participants were told about various perturbations to this system and were asked to judge effects on the components of the system. Evidence for the dissipation effect was found in their judgments. Judgments about other kinds of system should also be investigated to give a more complete assessment of this interpretation.

Ohm's p-prim was conceived within a deep and elaborate conceptual framework aimed at elucidating an intuitive sense of mechanism said by diSessa (1993) to underlie and account for much of our understanding of the physical world. Some elements of diSessa's framework are best regarded as contentious at present (see, for example, Chi & Slotta, 1993). Nevertheless, there is abundant evidence from other sources that ideas of force and resistance (in various guises) are fundamental both to the organization of meaning in language (Talmy, 1988) and to causal cognition (White, 1989, 1992b, 1995b; Shultz, 1982; Shultz, Fisher, Pratt & Rulf, 1986; Ahn, Kalish, Medin & Gelman, 1995). It is therefore possible that notions of force and resistance play a very general and fundamental role in our understanding of the world, in modeling physical systems, in organizing meaning in language, and in causal cognition in general. The present research provides an insight into the naive understanding of complex physical systems that may be general and powerful in application: although people may not possess a fully developed understanding of natural systems incorporating concepts such as negative feedback, they may possess a naive version of a feedback model in which equilibrium is maintained by the balance between influences and resistances.

To the extent that Ohm's p-prim captures the intuitive sense of mechanics, it may be applied in interpreting any kind of interaction between things. Thus, the minimal conditions for applicability of Ohm's p-prim are that at least two discrete entities be involved (one for force and one for resistance), and that some kind of change or action occurs, more specifically that one entity is seen as acting on the other or others in some way. Many events that involve two objects in interaction do not appear to evoke Ohm's p-prim. For example, diSessa (1983) discussed the case of a coin rolling around the edge of a second, fixed coin. A ball rolling along a floor would be another example. The salient feature of such interactions is the fixed and unchanging nature of one of the objects. Thus, although ball and floor interact, the floor is fixed and does not move: it is, so to speak, a context within which the ball behaves. As a first approximation, then, Ohm's p-prim may be evoked whenever one object not only acts (i.e., exhibits observable behavior) but also is seen as acting *on* another with some observable effect. (This way of putting it expresses the asymmetry that characterizes the naive conception of mechanics.) This is probably overinclusive: for example, the p-prim may not be judged applicable to interactions in which one thing burns or dissolves another. Further research would be necessary to ascertain what further conditions may limit the p-prim's applicability.

Other Interpretations

Notions of force are not confined to Ohm's p-prim. Caramazza, McCloskey, and Green (1981) and McCloskey (1983) have argued that naive conceptions of object motion resemble the medieval impetus theory, which has two main components: setting an object in motion involves imparting to it an internal force, "impetus," which tends to maintain its motion; and the impetus spontaneously dissipates over time. A notion similar to the latter appears in another p-prim proposed by diSessa (1983, 1993), termed "dying away." diSessa suggested that a notion of the spontaneous dying away of certain actions, such as the sound of a bell, is a phenomenological primitive. Among other things, it could explain the common misconception that a constant force is needed to maintain a constant velocity, and that a craft in outer space deprived of its means of propulsion will gradually coast to a halt. Both accounts can explain dissipation: a perturbation is interpreted as a source of impetus, but instead of encountering resistance the impetus has a natural tendency to dwindle with increasing distance from its source. Less impetus means less effect, so species more distant from the perturbation suffer less population change according to how much the impetus has diminished on its way.

If spontaneous dying away of impetus is responsible for the dissipation effect, however, it fails to explain the branching and terminal effects. The branching effect does not resemble anything in the impetus theory of object motion. Moreover the impetus theory of object motion would predict that judged change should be similar for terminal and nonterminal species at the same distance from the perturbation: if judged population change follows from a notion of spontaneous dying away of impetus, the amount of dissipation for a given perturbation should be the same for all species at the same distance from the perturbation. An account involving some notion of resistance is better able to explain the terminal effect, and therefore gives a better overall account of the naive analysis of food web dynamics.

The core of the Ohm's p-prim account is that an effect is a function of influence and resistance, being proportional to the amount of influence and negatively proportional to the amount of resistance. In application to food web dynamics, two kinds of resistance are hypothesized, intrinsic and extrinsic. Each species is presumed to have intrinsic resistance, probably reflecting adaptive characteristics such as the capacity to survive periods of food shortage, the capacity to make up numbers lost through predation by increased breeding rate, and so on. Nonterminal species are also assumed to have extrinsic resistance, a characteristic conferred by dynamics involving parts of the system on the far side of the species from the perturbation, in terms of the structure of the food web. These dynamics tend to maintain the equilibrium population level of the species, and thus act as a source of resistance to the influence of the perturbation. Terminal species lack this source of resistance because there are by definition no species on the far side of them from the perturbation. Other things being equal, therefore, terminal species tend to have less resistance to influence than nonterminal species do, and this explains why they undergo greater judged change.

Is it possible to account for the findings without recourse to the concept of resistance? One possible alternative appeals to a naive notion of conservation of influence.[3] Under this principle a perturbation introduces a quantity of influence that is conserved in interactions that take place within the food web. Thus, changing the population of a given species "uses up" a certain amount of influence. Dissipation would therefore result from the quantity of influence being reduced by successive interactions with species, so that there is less influence to act on more distant species. At a branch in the food web the amount of influence in each branch is reduced because conservation requires that the sum of the amounts of influence in each branch should not exceed the total amount prior to the branch. This accounts for the branching effect. One finding that is problematic for the conservation model, however, is that less change was judged for humans than for the animal species at the same location in the food web in Experiment 1 above. The notion of conservation of influence does not explain why one species should be judged less affected by a perturbation than another. The notion of resistance can account for this on the hypothesis that species have different properties that confer different amounts of intrinsic resistance.

The conservation model could account for the terminal effect. If some quantity of influence is drained off by species posterior to a nonterminal species, then there is less available to affect that species. Because there are no posterior species to drain off influence in the case of a terminal species, there is more influence available to effect it. Thus, by conservation, more change will be judged for terminal than for nonterminal species. This reasoning implies that, whether a species is terminal or not, the amount of influence available to affect it is determined in part by the number of species posterior to it in the food web. For example, from Figure 1, if there is a perturbation to P1, H1 has two posterior species and H2 has one, so judged influence should be greater for H2 than for H1. Evidence does not support this. The effect of number of species posterior to a given nonterminal species was investigated in the reconsideration of evidence (see above) and there was no evidence that it makes a difference. This counts against the conservation model and suggests that there is something different about being a terminal species. The notion of extrinsic resistance conferred by the equilibrium-maintaining dynamcis of interactions with posterior species appears best able to explain this, though more research is necessary before definite conclusions can be drawn.

A different kind of physical model could also be proposed.[3] Imagine a series of springs fixed to a flat surface and constrained to move vertically. Adjacent springs are connected by strings. If we take each spring to be a species and each string to be a connection in a food web, then this is a possible physical model of food web dynamics. The arrangement could, for example, mimic that in Figure 1. A perturbation would be equivalent to a force depressing one of the springs. A physicist's account of this system would probably not be the same as a lay person's because, as numerous investigators have demonstrated, lay concepts of mechanics are not identical to the laws of mechanics themselves (diSessa, 1983, 1993; Clement, 1983; McCloskey, 1983). However, dissipation would probably be predicted by both. If spring A is depressed and is connected by a string to spring B, spring B must be depressed less than spring A unless the string is perfectly rigid. Nothing flows from spring A to spring B. The force that depresses spring B is generated by differences in height between the springs. The model also predicts the terminal effect because a terminal spring is not held up by connections to any other springs and will therefore tend to be pulled down more than will springs with further connections to other springs.

The properties of the model do not match the observed tendencies in respect of branching, however. The spring model does yield a kind of branching effect. If spring B is connected to spring C, the connection to spring C effectively functions as a source of resistance, tending to hold spring B up while the string from spring A is tending to pull it down. (I hope physicists will excuse the rather loose language.) If spring B is directly connected to both spring C and spring D then it effectively possess more resistance because both connections tend to hold it up, and so it is not depressed so much, other things being equal. In other words, the branching effect acts on the location at which the branch originates, as well as on subsequent locations. This can be tested.

The original evidence for the branching effect was found in Problem 4 from White (1997), using the food web depicted in Figure 1. If the spring model is correct, then there should be less judged change for herbivore H1, at which a branch originates, than for H2, at which no branch originates. In fact the mean judged change for these two species was virtually identical, 67.97 and 67.72, respectively. In the present research there were several tests of the branching hypothesis, and the spring model prediction can also be tested in each case. In Experiment 2, Problem 2, the appropriate comparison is between C1 and H3 (see Figure 5). A significant difference in the predicted direction was found, $t(49) = 2.26$, $p < .05$. However, it was noted in the discussion to Experiment 2 that the support found for the branching hypothesis there could be explained as the outcome of a process of adjustment from the amount of change judged for the previous species en route, and the same explanation could apply here: the difference in means between the previous species, H1 and P2, respectively, was in fact greater in magnitude than the difference in means between C1 and H3. For this reason the observed difference does not give strong support to the spring model. In Experiment 2, Problem 3, the appropriate comparison is between P1 and P2 and no significant difference was found, $t(49) = 0.43$. In Experiment 3, Problem 1, the appropriate comparison is between A1 and A2 (see Fig. 7) and no significant difference was found, $t(39) = 0.13$. In Experiment 3, Problem 2, the appropriate comparison is between P1 and A3 and no significant difference was found, $t(39) = 0.22$. In Experiment 4 a lack of significant differences between species apart from that supporting the branching effect was reported in the results section for that experiment. On the whole, then, there is little or no evidence for the effect predicted by the spring model.

The spring model also fails in another respect: a spring is only reduced in height when a force is applied. When the force is removed, the spring tends to recover (most of) its original height. The perturbations studied in research on the dissipation effect have all been single events of restricted duration. People have, however, consistently been asked to judge stable changes, and “stable” has been explicitly defined as a change that naturally persists indefinitely unless interfered with in some way. The dissipation effect is a feature of these judgments of stable change. White (1998) compared judgments of population one year and ten years after a perturbation and found no difference. White (1999) examined change over a series of successive time periods and found that the cumulative dissipation effect actually increased over time, with the biggest changes occurring in the first time period judged. The dissipation effect is therefore not restricted to the time period of the perturbation, but is judged to be an enduring change in the equilibrium state of the food web. In this respect it is more akin to a stamp depressing a lump of soft clay than a force depressing a spring.

In summary, Ohm’s p-prim appears superior to other possible accounts in its ability to account for the observed judgmental phenomena. However the present findings do not rule out the possibility of other kinds of physical models or analogies. There are several ways in which research could shed more light on this. Developmental studies could elucidate changes in judgmental tendencies with age and tie them to other cognitive developmental phenomena (e.g., Karmiloff-Smith, 1984). Detailed case studies involving think-aloud or written protocols could reveal explicit physical models used by judges, as in diSessa (1982). Studies of lay reasoning about concrete and familiar physical models would also reveal the extent of similarities between reasoning about those models and reasoning about food webs. People could, for example, be asked to make judgments about arrangements of springs connected by strings to ascertain whether a naive version of the spring model could be informing food web judgments.

In conclusion, therefore, the present research supports a domain-general interpretation of the naive analysis of food web dynamics in terms of the concepts of influence and resistance applied to complex physical systems. Other interpretations may also be viable, but the influence and resistance model provides a conceptual framework for the understanding of causal judgments about complex physical processes that can generate many predictions for future research. For example it implies that the dissipation effect should be a general feature of judgments of change in complex physical systems. There is already some evidence in support of this (White, 1998, Experiment 3), and there are many possible opportunities for collecting more.

VIII. CONCLUDING REMARKS

Kempton (1986) pointed out that naive theories about physical systems have implications for behavior. The way his participants treated the control of heat in their homes was determined in part by the theory of heat control they possessed. Those that possessed one theory tended to behave more economically than those that possessed the other theory. Changing theories of heat control could make a difference measurable in billions of dollars within the United States, never mind the rest of the world, with correspondingly profound implications for power generation and resource depletion.

The implications of naive models of food web dynamics are surely even greater. Actions on the natural environment such as pesticide spraying and the discharge of industrial waste products into rivers are governed by political, economic, and motivational factors, but the influence of cognitive factors is unlikely to be negligible. Dissipation is not a usual feature of effects of perturbations to food webs. Consequently, people may act on the basis of inappropriate beliefs about the likely consequences of their interventions, and may be slow to realize the scale of the effects that run counter to common tendencies in their reasoning. If people believe that dissipation is characteristic of the effects of perturbations, then they believe that species remote from perturbations in terms of the structure of the food web are relatively little affected by them. Detecting an effect that is contrary to dissipation and identifying its cause is very difficult, because the complexity of interactions even in quite small food webs is incalculable and because such effects are contrary to naive expectation.

Intervening in natural systems such as food webs while in the grip of a naive belief about the effects of one's intervention is therefore extremely dangerous. The destructive effects of the intervention on species remote from its location, and the general disruption of the food web, may be much greater and more difficult to repair than anyone could anticipate. Naive models of food web dynamics could therefore be responsible for unintentional and unanticipated but profound and irreversible damage to ecosystems, with equally profound implications for the world in general.

NOTES

1. In the absence of more specific knowledge about how people conceptualise food web dynamics, the comparatively neutral term "influence" is used here to avoid the connotations of terms such as "force" and "energy."
2. Although tests of the dissipation effect ignore the sign of the judged change, consensus on the direction of change that will occur tends to be high (see also White, 1997). For example, in Experiment 2, Problem 2 (P1 -50), the following results were found. For each of species H1, C1, C2, H2, and C4, all 50 participants judged decrease. For P2, 48 judged increase and the remaining 2 judged no change. For H3 and C5, 47 judged increase and 3 judged no change. For C3, 49 judged decrease and 1 judged increase. Lower rates of consensus are sometimes observed (approximately, 80% in one direction, 10% in the other, and 10% no change) but are the exception.
3. I am grateful to Andrea diSessa for this suggestion.

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