



Thought for Food: Imagined Consumption Reduces Actual Consumption

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Science **330**, 1530 (2010);
DOI: 10.1126/science.1195701

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15. By taking the ratio of Os concentration in the primitive upper mantle (~3.3 ppb) against the average concentration of all three chondrite groups weighted equally (~660 ppb) (12), we estimate that the terrestrial mass addition fraction is 0.005. Assuming the mass of Earth's mantle is 4.0×10^{24} kg, the terrestrial mass addition requirement is 2.0×10^{22} kg. A similar calculation can be made for Mars. If HSEs in the martian mantle are $0.7 \times$ the terrestrial concentration [for example, 2.4 ppb Os; consistent with the current database for shergottites (8)], and the martian mantle comprises ~80% of the mass of the planet (5.1×10^{23} kg), the martian mass addition requirement is $\sim 2.0 \times 10^{21}$ kg. This yields a ratio for terrestrial/martian additions of 10. For the Moon, assuming HSE abundances in the lunar mantle are ≤ 20 times lower than in the terrestrial mantle (9, 10), we obtain a maximum Os concentration of 0.16 ppb. Assuming the mass of the lunar mantle is 6.9×10^{22} kg and the same average chondritic concentration for the impactors, we obtain a lunar mass addition requirement of 1.7×10^{19} kg. This yields a ratio for terrestrial/lunar additions of 1200.
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24. Projectiles were randomly selected from a size distribution $dN \propto D^{-q}dD$. The range of D was set to 200 to 4000 km; this was designed to provide some flexibility in case the largest projectiles deliver only ~80 to 90% of their HSEs to the mantle. A successful run had an Earth/Moon mass ratio >700 with the accreted mass on Earth set to $>2.0 \times 10^{22}$ kg. The Earth/Moon impact number flux ratio was set to 20 (14, 18, 19). The sizes of the largest impactors, as well as the number of objects hitting each world within a given run were treated as variables.
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49. We thank A. Barr, R. Canup, R. Citron, L. Dones, H. Levison, J. Jones, H. Nekvasil, A. Morbidelli, D. Minton, S. Mojzsis, G. J. Taylor, and D. Vokouhlicky for many useful discussions and two anonymous reviewers for constructive reviews. W.F.B.'s and D.N.'s participation was supported by NASA's Lunar Science Institute through a grant to the Center for Lunar Origin and Evolution at the Southwest Research Institute in Boulder, Colorado. R.J.W.'s and J.M.D.'s work was supported by NASA's Lunar Science Institute through contract NNA09DB33A to the Center for Lunar Science and Exploration at the Lunar and Planetary Institute in Houston, Texas, and the NASA Astrobiology Program through grant NNG04G49A to the Goddard Center for Astrobiology in Greenbelt, Maryland.

24 August 2010; accepted 10 November 2010
10.1126/science.1196874

Thought for Food: Imagined Consumption Reduces Actual Consumption

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The consumption of a food typically leads to a decrease in its subsequent intake through habituation—a decrease in one's responsiveness to the food and motivation to obtain it. We demonstrated that habituation to a food item can occur even when its consumption is merely imagined. Five experiments showed that people who repeatedly imagined eating a food (such as cheese) many times subsequently consumed less of the imagined food than did people who repeatedly imagined eating that food fewer times, imagined eating a different food (such as candy), or did not imagine eating a food. They did so because they desired to eat it less, not because they considered it less palatable. These results suggest that mental representation alone can engender habituation to a stimulus.

People believe that thinking about a desirable food or drug sensitizes one to it, increasing their hedonic response to the stimulus (1). Indeed, picturing oneself eating a delicious steak elicits an increase in salivation

and the desire to eat it (2), and imagining the sight or smell of a burning cigarette increases smokers' craving (3). The increased desirability of imagined stimuli seems to similarly affect behavior: Children have greater difficulty resisting

the impulse to eat one marshmallow immediately in order to eat two a few minutes later if they can see the marshmallow while they wait (4). Although much evidence appears to support this common intuition (4–7), its accuracy is quite puzzling, because it seems to contradict decades of research examining the overlap between direct perception and mental imagery.

Perception and mental imagery differ in their source (the senses and memory, respectively), but there is great overlap within modalities. Both engage similar neural machinery and similarly affect emotions, response tendencies, and skilled motor behavior (8–11). The thought of a spider crawling across one’s leg can produce the same increases in perspiration and heart rate that would result from a spider’s actual presence (5). Even the mere simulation of a motor skill can result in an improvement in its subsequent performance (9, 12). Because perception and mental imagery tend to elicit similar responses, one would expect that thinking about the consumption of a stimulus should habituate one to it.

Habituation denotes the decreased physiological and behavioral responses induced by extended or repeated exposure to a stimulus (13–15). A 10th bite of chocolate, for example, is desired less than the first bite. People habituate to a wide range of stimuli, from the brightness of a light to their income (16, 17). Habituation to food occurs too quickly for it to result from digestive feedback, so it is commonly thought to occur as a result of top-down cognitive processes (such as beliefs, memories, or expectations) or pre-ingestive sensory factors (such as texture or smell) (13, 18). Given the overlap in perception and mental representation, thinking about the consumption of a food should lead people to habituate to it.

Why then might people exhibit sensitization when thinking about a stimulus? We suggest that the sensitizing effect of imagery found in previous research may be due to the kind of imagery it has used: having participants vividly imagine a single exposure to a stimulus or associated cues. This form of imagery is more analogous to the initial exposure to a stimulus that whets the appetite and induces sensitization than to the repeated experience of a stimulus necessary to engender habituation (13). We suggest that mentally simulating an experience that is more analogous to repeated exposure (such as repeatedly imagining the consumption of units of a food) might engender habituation to the stimulus. We report five experiments testing whether repeated mental simulation of experiencing a stimulus, alone, can engender habituation. Specifically, we examined the effects of repeatedly imagining the consumption of a food on subsequent consumption of that food.

Our first experiment ($N = 51$ participants) tested whether repeatedly imagining the consumption of a food would increase or decrease the amount of that food that people would subsequently consume. All participants imagined performing 33 repetitive actions, one at a time, to hold effort constant across conditions. Controls imagined inserting 33 quarters into a laundry machine. (This served as a control task because it involves motor actions similar to those involved in eating M&M chocolate candies.) Participants in a three-repetition condition imagined inserting 30 quarters into a laundry machine and then imagined eating 3 M&M’s. Participants in a 30-repetition condition imagined inserting 3 quarters into a laundry machine and then imagined eating 30 M&M’s. Then all participants ate ad libitum from a bowl containing 40 g of M&M’s as preparation for a “taste test” (19). The M&M’s were removed when participants indicated they were finished eating. The amount of food that each participant ate was surreptitiously measured on a digital scale after the experiment. In all experiments, condition assignment was random.

A between-subjects analysis of variance (ANOVA) showed that the amount of M&M’s eaten by participants was influenced by the imagination induction, $F(2, 46) = 3.61, P < 0.05$ (Table 1). Planned comparisons revealed that participants in the 30-repetition condition ate significantly fewer M&M’s than did participants in the three-repetition condition and participants in the control condition, $F(1, 46) = 5.81, P < 0.05$ and $F(1, 46) = 4.50, P < 0.05$, respectively (Table 1). The amount eaten by participants in the three-repetition and control conditions did not differ significantly, $F < 1$, so the imagination induction did not sensitize participants to the food. Rather, repeatedly imagining the consumption of a food habituated participants to the food.

To ensure that the results of the previous experiment were due to imagined consumption rather than to the control task, in experiment 2

($N = 51$ participants), we orthogonally manipulated the experience that participants imagined (eating M&M’s or the control task) and the number of times that experience was imagined (3 or 30 repetitions). A 2(repetitions: 3, 30) \times 2(behavior imagined: eating, control) between-subjects ANOVA yielded a significant interaction, $F(1, 47) = 4.65, P < 0.05$. Planned comparisons revealed that participants who imagined eating 30 M&M’s subsequently consumed fewer M&M’s than did participants who imagined eating 3 M&M’s, $F(1, 47) = 4.24, P < 0.05$. Repetitions of the control task performed did not affect subsequent consumption of M&M’s, $F(1, 47) = 1.05, P > 0.30$. No main effects were found, F ’s < 1 (Table 1).

Experiments 3 to 5 tested whether habituation or an alternative process causes repetitive imaginary consumption of a food to reduce subsequent consumption of that food. Experiment 3 ($N = 68$ participants) tested whether one must repeatedly simulate consumption of the food or whether repeated exposure to the stimulus [priming (20)] is sufficient to reduce subsequent food intake. Participants imagined eating 3 or 30 M&M’s (simulating consumption) or imagined placing 3 or 30 M&M’s into a bowl (priming) before consuming the candy ad libitum, as in the previous experiments.

A 2(repetitions: 3, 30) \times 2(behavior imagined: eating M&M’s, moving M&M’s) between-subjects ANOVA on the amount of food consumed yielded a significant interaction, $F(1, 64) = 11.17, P < 0.05$. Planned comparisons revealed that participants who imagined eating 30 M&M’s consumed significantly fewer M&M’s than did participants who imagined eating 3 M&M’s, $F(1, 64) = 6.10, P < 0.05$; whereas participants who imagined placing 30 M&M’s into a bowl consumed significantly more M&M’s than did participants who imagined placing 3 M&M’s into a bowl, $F(1, 64) = 5.11, P < 0.05$. No main effects were found, F ’s < 1 (Table 1). The results suggest that repetitive priming is not the process by

Table 1. Mean grams of the food consumed ad libitum after the imagery induction. Values are ± 1 SD from the mean. Means within rows that do not share the same symbol (* or †) differ significantly ($P < 0.05$). Each M&M weighed approximately 0.8 g; each cheese cube weighed approximately 4.5 g.

Imagery induction	Repetitions		
	0	3	30
Experiment 1 (food consumed: M&M’s)			
Eating M&M’s	4.08* \pm 0.33	4.18* \pm 3.26	2.21† \pm 0.48
Experiment 2 (food consumed: M&M’s)			
Manipulating quarters		4.31* \pm 0.78	5.55* \pm 3.86
Eating M&M’s		5.57* \pm 0.90	3.23† \pm 2.20
Experiment 3 (food consumed: M&M’s)			
Moving M&M’s		3.87* \pm 0.60	7.00† \pm 0.54
Eating M&M’s		7.59* \pm 4.45	4.28† \pm 3.05
Experiment 4 (food consumed: cheese)			
Eating M&M’s		9.47* \pm 0.98	11.15* \pm 0.82
Eating cheese cubes		11.25* \pm 0.27	6.36† \pm 0.91
After test (predicted consumption: cheese)			
Eating M&M’s		12.53* \pm 2.61	13.60* \pm 2.17
Eating cheese cubes		13.41* \pm 1.81	19.21† \pm 4.01

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which the repetitive imaginary consumption of a food reduces subsequent food intake. Rather, repetitive priming appeared to sensitize participants to the food (21).

Habituation is stimulus-specific. Habituation to a food leads to diminished consumption of that food without much affecting the consumption of other foods (15, 18). To further test whether the effect of imaginary consumption engendered habituation or merely primed a feeling of “fullness,” participants in experiment 4 ($N = 41$ participants) imagined eating the food they subsequently consumed (cheddar cheese) or imagined eating a different food (M&M’s) before consuming cheddar cheese.

Participants imagined eating 3 or 30 cheddar cheese cubes or M&M’s and then ate ad libitum from a bowl containing 40 g of cheddar cheese cubes. A 2(repetitions: 3, 30) \times 2(food imagined: cheddar cheese, M&M’s) between-subjects ANOVA on the amount of cheese that participants consumed yielded a significant interaction, $F(1, 37) = 4.99, P < 0.05$. Planned comparisons revealed that participants who imagined eating 30 cheese cubes consumed less cheese than did participants who imagined eating 3 cheese cubes, $F(1, 37) = 5.14, P < 0.05$. In contrast, participants who imagined eating 3 M&M’s or 30 M&M’s did not differ significantly in the amount of cheese they consumed, $F < 1$. No main effects were found, F ’s (1, 37) $< 1.19, P$ ’s > 0.28 (Table 1). The stimulus-specific effect of imagined consumption provides further evidence that habituation is the process by which repetitive imaginary consumption of a food leads to a reduction in its subsequent intake.

To ensure that the results of experiments 1 to 4 were not due to experimental demand, we described the design of experiment 4 to a new sample of participants ($N = 80$), who predicted average cheese consumption in each of its four conditions. Predictors correctly anticipated that

the imagined consumption of M&M’s did not influence the actual subsequent consumption of cheese, $t(79) = 0.66, P = 0.51$, but incorrectly predicted that participants who imagined eating 30 cubes of cheese would consume more cheese than would participants who imagined eating 3 cubes of cheese, $t(79) = 3.09, P < 0.01$; within-subjects ANOVA yielded a significant interaction, $F(1, 79) = 9.23, P < 0.01$ (Table 1).

Two psychological processes with distinct neural substrates appear to regulate food selection and intake. One process entails the hedonic responses to the food (liking or palatability) and may diminish intake through sensory-specific satiety (18). The other entails the motivation and appetitive drive to obtain it (wanting) and diminishes intake through habituation (15, 22, 23). In experiment 5 ($N = 81$ participants), we used a standard procedure to test changes in liking and wanting (23–25) to identify the process by which imagined consumption reduces food intake. Participants rated their liking for the imagined food before and after an imagination induction and played a reinforcement game, a measure of habituation (13, 15, 23–25). (Note that this method tested whether repeatedly imagining the consumption of a food leads one to feel disgusted by the food, which could also diminish consumption.)

First, all participants rated how much they liked cheddar cheese on a seven-point scale with endpoints: dislike extremely (1) and like extremely (7). Then, they imagined 33 repetitive tasks. Participants in a three-repetition condition imagined performing 30 repetitions of the control task (as in experiment 1) and then imagined eating 3 cheddar cheese cubes. Participants in a 30-repetition condition imagined performing three repetitions of the control task and then imagined eating 30 cheddar cheese cubes.

Then, all participants played the reinforcement game: Participants were shown a picture

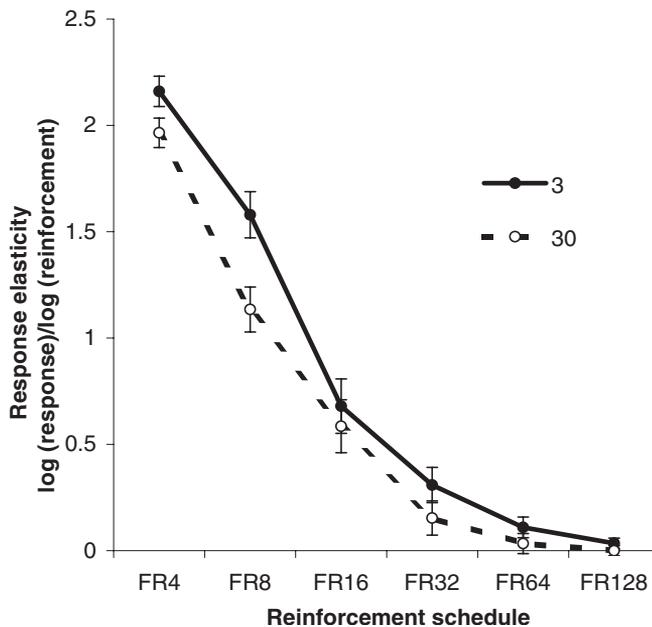
of a cheddar cheese cube and a STOP sign; they could collect points by clicking on the cheddar cheese cube. The game began with a fixed-ratio reinforcement schedule of 4 (FR4), in which every fourth click earned a point. Every time participants earned five points, the reinforcement ratio was doubled, progressing through FR8, FR16, FR32, FR64, and FR128. Participants could end the game at any time by clicking the stop sign. For each three points earned in the game, participants received one cheddar cheese cube at the end of the experiment. At the end of the game, participants re-rated how much they liked cheddar cheese on a scale identical to the scale used in the beginning of the experiment.

We calculated the difference between liking ratings before and after the imagination task to create an index of change in liking, and log-transformed responses in the reinforcement game to create an index of wanting. A 2(repetitions: 3, 30) \times 2(determinant: wanting, liking) mixed ANOVA with repetitions imagined as a between-subject factor and determinant as a within-subjects factor yielded a significant main effect for determinant $F(1, 66) = 637.10, P < 0.01$, and a marginally significant main effect for repetition, $F(1, 66) = 3.00, P < 0.1$, which were qualified by a significant interaction, $F(1, 66) = 4.82, P < 0.05$. Planned comparisons revealed that participants who imagined eating 30 cheese cubes clicked fewer times for cheese cubes in the reinforcement game ($M_{\log \text{ response}} = 3.68 \pm 1.40$) than did participants who imagined eating 3 cheese cubes ($M_{\log \text{ response}} = 4.35 \pm 1.02$), $F(1, 66) = 5.01, P < 0.05$. No difference in the change of liking was observed between the two conditions ($M_{\Delta \text{ three-repetitions}} = 0.00 \pm 0.87$; $M_{\Delta \text{ thirty-repetitions}} = 0.03 \pm 0.51$), $F < 1$.

Response elasticities [responses per unit price (26)] were then computed as $[\log(\text{number of responses emitted during a specific reinforcement schedule})/\log(\text{number of reinforced responses during that reinforcement schedule})]$ and are displayed in Fig. 1. A 2(Repetitions: 3, 30) \times 6(Reinforcement schedule: FR4–FR128) mixed ANOVA with repetitions as a between-subject factor and reinforcement schedules as a within-subject factor revealed that response elasticities declined linearly as reinforcement schedules progressed, $F(5, 62) = 315.08, P < 0.001$. As revealed in our previous analysis, participants who imagined eating 30 cheese cubes were less motivated to earn points toward cheese cubes than were participants who imagined eating 3 cheese cubes, $F(1, 66) = 4.69, P < 0.05$. There was a marginally significant repetitions \times reinforcement schedule interaction, $F(5, 62) = 2.31, P < 0.1$. These results suggest that imagined consumption of a food decreased its subsequent consumption through habituation because it diminished the degree to which people wanted the food; imagined consumption did not appear to affect how much they liked it.

Together, the results show that repeatedly imagining the consumption of a food leads people to habituate to it. Participants who imagined con-

Fig. 1. Motivation to earn points for cheese (expressed as response elasticity) as a function of the number of cubes of cheese (3 versus 30) that participants had imagined eating and fixed-ratio reinforcement (for example, in FR4, every fourth response was reinforced). Error bars represent ± 1 SEM.



suming more of a food were subsequently less motivated to obtain it than were participants who imagined consuming less of the food. The influence of the imagery induction on food consumption was stimulus-specific: It reduced the consumption of the food that participants imagined eating but did not affect the consumption of other foods. Finally, repetitively imagining the consumption of the food reduced wanting (the appetitive or motivational drive) for the food. Participants who imagined consuming more of the food subsequently expended less effort to obtain it.

These findings have important implications for three fields of research. First, the results suggest that mental imagery alone can engender habituation to a stimulus. In addition to its theoretical importance, this finding may allow for the development of more effective interventions to reduce cravings for unhealthy food and drugs and diminish phobic reactions to fear-inducing stimuli. Second, it has long been debated whether pre-ingestive sensory stimulation is required for habituation to occur (13, 27–29). Previous experiments in this vein have suffered from the confound of simultaneously enacting top-down processes and pre-ingestive sensory stimulation (participants ate or smelled the food to which they habituated). Mental imagery is considered a top-down cognitive process (10, 30). Thus, the results show that top-down processes can enact habituation in the absence of pre-ingestive sensory stimulation. Finally, the results show that

repeatedly simulating an action can trigger its behavioral consequents (2). Rather than increase the likelihood of enacting the simulated behavior (eating), simulation evoked the consequences of the behavior (habituation). The difference between actual experience and mental representations of experience may be smaller than previously assumed (10).

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31. This work benefited from financial support from a grant to C.K.M. from the Berkman Faculty Development Fund at Carnegie Mellon University. We thank A. Kim, K. Khanna, M. Fei, L. Mosca, M. Christian, and Center for Behavioral Decision Research summer interns in 2008 and 2009 for help with the data collection. We thank C. Janiszewski, D. Kahneman, G. Loewenstein, B. Rolls, and L. Williams for helpful comments.

Supporting Online Material

www.sciencemag.org/cgi/content/full/330/6010/1530/DC1
SOM Text
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27 July 2010; accepted 28 October 2010
10.1126/science.1195701

Sex Determination in the Social Amoeba *Dictyostelium discoideum*

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The genetics of sex determination remain mysterious in many organisms, including some that are otherwise well studied. Here we report the discovery and analysis of the mating-type locus of the model organism *Dictyostelium discoideum*. Three forms of a single genetic locus specify this species' three mating types: two versions of the locus are entirely different in sequence, and the third resembles a composite of the other two. Single, unrelated genes are sufficient to determine two of the mating types, whereas homologs of both these genes are required in the composite type. The key genes encode polypeptides that possess no recognizable similarity to established protein families. Sex determination in the social amoebae thus appears to use regulators that are unrelated to any others currently known.

Most eukaryotes are sexual, but little is known in molecular detail about sex across most branches of the eukaryotic tree. One aspect, the genetic basis of sex determination, is well understood in several animal,

fungal, and plant lineages (1–5), but across the protozoan kingdoms we know little, and nothing in comparable detail. The social amoebae are members of the Amoebozoa and have an unusual sexual cycle that leads to the formation of dormant walled macrocysts (6) (Fig. 1, A and B). To produce a macrocyst, a pair of haploid amoebae of different sexes fuse (7) to form a diploid zygote, which then attracts surrounding haploid cells (8). These help to lay down external layers of cellulose around the developing mass of cells before being cannibalized by the zygote (9). After a period of dormancy,

the cyst germinates, releasing haploid progeny that arise most likely after meiosis and multiple mitoses (10). The population genetics of wild isolates indicate that mating and recombination are probably frequent in the wild (11).

The most-studied species of social amoeba, *Dictyostelium discoideum*, is notable for having three sexes [hereafter called mating types I, II, and III [supporting online material (SOM) text S1], as well as uncommon self-fertile homothallic strains (12–14). Each of the three sexes can pair with each of the other two but not with itself, giving three possible classes of zygote: type I/type II, type I/type III, and type II/type III. Although several genes are known to be involved during the sexual cycle (15), the determinant of mating type has proved elusive. Genetic analysis suggested that mating type is stable and is determined by a single locus with two or more alleles (10, 14, 16). We argued that it might be possible to identify this postulated locus by searching for genes that are present in any member of one mating type but absent or highly diverged in any member of another. For this purpose, we performed comparative genomic hybridizations using DNA microarrays composed of probes for around 8500 of the 10,500 predicted genes in the sequenced type I *D. discoideum* genome (17).

We analyzed 10 strains derived from independent wild isolates (table S1) using this micro-

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