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On Making Decisions: from Molecules to Mammals*

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Abstract

Decisions can be measured in bits of information. In turn, bits measure selections between biological states that can be represented as spheres in a high dimensional coding space. The spheres do not intersect when decisions are distinct but instead are tightly packed together and just kissing, like gumballs in a gumball machine. In this case, the isothermal efficiency of the process is 70%. Reversing this logic, when a system has a 70% efficiency this implies that its functional states are distinct. The EcoRI molecule and a domestic cat named Molly are used as examples to demonstrate the 70% effect. Evidently these ideas apply at all levels of living beings and might provide a way to measure degrees of consciousness. If a molecule and a mammal both make decisions in the same way, what are our obligations for treating them kindly as sentient beings?

Keyphrases

Theoretical biology, information bits, hyperspheres, isothermal efficiency, decision making, EcoRI molecule, domestic cat, 70% effect.

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Molecular Decision Making

What is a decision? What does it mean to make choices? In this short note I provide a simple answer: if a process created by an organism or a machine can be measured in bits, then the bits can be considered to be decisions (Pierce 1980). When the selection of one possibility from several possibilities is made, that is the decision process.

Let's simplify the problem all the way down to the molecular level.

Consider a classical macroscopic microbiology experiment that led to a very important discovery. Say that I have two strains of the human gut bacterium *Escherichia coli* in liquid nutrient broth in Erlenmeyer flasks. I also have a vial containing a virus called λ that can infect *E. coli*. I warm up some agarose (a gel like substance) in a test tube and put a drop of strain A into the tube. I swirl the tube around to mix and then pour it into a nutrient agarose filled Petri plate where it hardens. I do the same for strain B. When these plates are put into a 37°C incubator, the next morning the agarose will have a cloudy yellowish surface. This is a 'lawn' of bacteria. Now I take the virus and make a series of tenfold dilutions (1 microliter into 9 microliters of saline, repeat with a fresh pipette). Then I repeat the experiment of plating out the bacteria but each Petri plate gets 1 microliter of a different dilution of virus. The next morning for strain A I see, at an appropriate dilution of the virus, hundreds of little holes in the lawn of bacteria. These viral plaques are places where a single virus landed, attached to a bacterium, injected its DNA, copied itself inside the bacterium and about 150 viruses burst out, as in the movie Alien. The viruses are called bacteriophages since the ancient Greek word 'phagein' ($\varphi\alpha\gamma\epsilon\iota\tilde{\nu}$) means 'to eat'. But even though strain B is an *E. coli* that could even mate with strain A, very few viruses grew on those plates. How do we explain this result?

Hundreds of genetic and biochemical experiments later we learn that *E. coli* strain B (RY13) uses a protein called EcoRI to attack invading DNA. EcoRI is a 'restriction enzyme', so called because it restricts the growth of bacteriophage λ and other viruses (Modrich et al. 1976; Roberts 2005; Pingoud et al. 2014). The mechanism of restriction happens when the virus injects its DNA into the *E. coli* cell. At that time the DNA is naked. EcoRI loosely binds to the DNA and scans along it looking for the sequence GAATTC. When EcoRI finds this specific sequence, it binds more strongly and cuts the DNA (Fig. 1). As a result the linear λ DNA is cut 5 times and so falls into 6 pieces.[1] The virus dies when those

[1]The ability of restriction enzymes to specifically cut DNA launched the field of

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are chewed up by the RecBCD enzyme (Dillingham et al. 2008).[2]

Decisions Involve Information and Energy

We need to investigate two distinct aspects of how EcoRI works to understand the decision process deeper. The first aspect is the information involved and the second is the energy.

To begin imagine EcoRI looking at DNA at the first position of GAATTC. The enzyme surface was programmed by evolution to detect a 'G'. EcoRI will only bind if there is a G, but in general during a search there are any of the four bases A, C, G or T. So as it binds to its site EcoRI picks one base in 4. Likewise if I were to hand you a coin that has a heads side and a tails side, you have to decide which of the two possibilities you got. That decision, a choice between two equally likely possibilities, requires one 'bit' of information (Pierce 1980). Claude Shannon developed information theory to account for non-equal probabilities (Shannon 1948; Schneider 2013), but we don't need that complication for this paper, although it does apply to more complicated binding sites (Schneider, Stormo, et al. 1986; Schneider and Stephens 1990).

When EcoRI picks one of the 4 bases, that requires 2 bits. The easiest way to see this is to arrange the four bases into a square: $\begin{bmatrix} A & C \\ G & T \end{bmatrix}$. We then ask two questions: 1. is the base on the top row? 2. Is the base in the left column? Each answer gives us one bit of information. You should convince yourself that you do not need 3 questions to determine the base.

Since there are 6 bases in GAATTC, EcoRI does these selections 6 times for a total of 12 bits. That this is a molecule making a decision is emphasized by noting that the DNA and protein involved contain about 9,200 atoms.

Now we are ready to consider the second aspect of the decision process, how energy is used. First let's consider the coin again to clarify how the information is related to the energy. Suppose I am holding a coin 10 cm above a table. When I set the coin on the table, you can read whether it is heads or tails to get one bit of information from me. So I have to allow the potential energy and any kinetic energy in the coin to dissipate into the room for it to be stable on the table. If I drop the coin, at the instant it hits the table it still has kinetic energy and so could bounce. So both kinetic and potential energy need to dissipate as a clinking sound and finally heat in the room. You get one bit of information from me.

Now consider if I start with the coin at 20 cm above the table. In this case twice the energy must be dissipated, yet you still get only one bit of information. So there is an inequality in the relationship between the energy dissipated and the information you gain. At 20 cm the process is less efficient than it was for 10 cm because more energy was dissipated for the bit of information you gained.

When EcoRI binds to the DNA strongly at GAATTC, the formation of 12 hydrogen bonds (McClarin et al. 1986) releases energy to the surroundings. This energy rapidly dissipates away from the DNA/protein interface in a few picoseconds since sound takes about about 1.3 picoseconds to traverse a double stranded DNA molecule (Mackenzie 1981). Eventually enough thermal noise will gather together at the interface to kick the EcoRI off the DNA again. The ratio of on to off states is the binding constant and molecular biologists have measured it to be about $K_D = 1.6 \times 10^5$ (Clore et al. 1982).

To get the number of bits from the binding energy turns out to be surprisingly trivial - just take the log base 2 of the binding constant (Schneider 2010a). In this case, $\log_2 1.6 \times 10^5 = 17.3$ bits.

This is a little disconcerting. We know from molecular biology experiments that EcoRI binds GAATTC and so makes 12 bits of decision. But the computation from the energy gives a result that is higher, 17.3 bits. So EcoRI is not 100% efficient, it is only $12/17.3 = 69\%$ efficient. Efficiencies near 70% turn out to be common in molecular interactions and this number appears all across biology (Schneider 2010a; Schneider 2010b; Schneider 2023).

Macroscopic Decision Making

One day just as I left for work, I met a young *Felis catus*. When I came home she was still there so with a peeping sound I asked her to come with me to other buildings and she did. We could not find her original home. A nice lady saw me bringing her around and brought some food. At that point she took possession of me as her human and I named her Molly. Perhaps a week later I realized that her middle name was Cule. (I kid you not!) She was a rather smart cat—for example she could control a ball rolling across the floor at high speed. I could not understand how she did it until I caught her on video, slowed it down, and saw that she was placing one foot down, kicking with the other and alternating like a soccer player! She was also a bean bag artist. Arrange the surface in any arbitrary pattern and she would fit herself to it (Fig. 2). All of these stories indicate that Molly was an intelligent being who made interesting discoveries and inventions.

Having been a stray, Molly always wanted to go outside. So she would go to the door and wait for me to open it. Then she would either go out or not. Eventually I started recording her decision; the running fraction of times she would go out is graphed in Fig. 3. Remarkably the curve fluctuates around 70%. Obviously this experiment could be replicated by other pet owners.

When Molly went to the door presumably she had many factors in mind. Is it cold or windy out? Am I actually hungry and should I eat instead of going out? Maybe I'm sleepy and would rather rest on the beanbag. Each of these factors fluctuates. My theoretical model of the decision process (Schneider 2023) is that these fluctuations are the sum of many small impulses, which by the central limit theorem of probability theory implies that the means have a Gaussian distribution. A pair of independent Gaussians has a circular distribution (Schneider 2006) and many of them form a high dimensional sphere (Schneider 1991). Such a '*hyper*sphere' represents the biological state. For Molly there were two states, to go in or to go out. These states are distinct and so the spheres do not intersect. In this circumstance the highest efficiency possible is $\ln 2 \approx 70\%$ (Schneider 2010a; Schneider 2010b; Schneider 2023). So the data showing that Molly made decisions resulting in a 70%/30% spread supports the idea that her biological states can be represented as spheres in a high dimensional space. When she makes a decision, she is selecting one of those states.

genetic engineering.

[2] Why don't the EcoRI restriction enzymes chew up the bacterial DNA too? It turns out that *E. coli* has another enzyme called a methylase that adds a methyl group -CH_3 to the first A of GAATTC (Frederick et al. 1988). This modification prevents EcoRI from cutting the DNA. In contrast, the fresh invading DNA of the λ virus does not have this protection. However, a few viruses manage to get methylated before being destroyed. These appear at frequencies much higher than would be required for mutation of the viral DNA, so their survival is by a different mechanism than mutation. Once a virus has been methylated, it can survive and produce a plaque visible to humans. Viruses isolated from the plaque should be able to grow on strain B.

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EcoRI also has hyperspherical states that distinguish GAATTC from the $4^6 - 1 = 4095$ other possible 6 base DNA sequences. In that case, the noise is obviously Gaussian thermal noise. We discovered that EcoRI and other restriction enzymes work in a 24 dimensional space (Schneider and Jejjala 2019). This is remarkable because the best way of packing high dimensional spheres together is the 24 dimensional Leech lattice (Leech 1967; Conway et al. 1998; Sloane 1998; Cohn et al. 2017). Apparently EcoRI is using the optimal way of packing its states together.

So living things ranging from a tiny restriction enzyme molecule to an entire mammal 10 million times larger both follow the same mathematical information theory. In both cases, they make decisions and express the 70% effect. This occurs because of Gaussian noise in the high dimensional space of decision-making (Schneider 2023).

The Mathematics of Consciousness

Perhaps the largest unanswered question in all of science is what is consciousness (Klein 2026; Nagel 1974; Tononi and Edelman 1998). Reams have been written thrashing the obvious (Kuhn 2024). I am conscious, and this is a subjective experience. I do not have access to your consciousness but out of politeness, fear of utter loneliness and a strong dose of evolutionary theory, I assume that you and Molly are also subjectively conscious. A theory of consciousness by Tononi *et al.* (Tononi, Albantakis, et al. 2023) proposes several axioms, one of which is that experiences are '*unitary*' - a single thing. Thermal noise and hence Gaussian distributions are universal in biology, and undoubtedly there are many dimensions to the conscious state because this makes the hyperspheres sharper (Schneider 1991) which means there are fewer decision errors (Bayne et al. 2016; Walter 2021; Pálenik 2024) as with most biology (Schneider 2023). This suggests that the subjective unitary conscious experience might be modeled as a single Shannon hypersphere. Perhaps this multidimensional concept will be useful for understanding brain states. For example, the problem of ordering of consciousness states (see figure 1D of (Bayne et al. 2016)) discussed by Pálenik and others (Pálenik 2024) is clarified. High multidimensional hypersphere brain states could pack together like gumballs in a gumball machine (Schneider 1991; Schneider 2010a; Schneider 2006; Schneider 2023) as in the 24 dimensional Leech lattice (Leech 1967; Conway et al. 1998; Sloane 1998; Cohn et al. 2017) that EcoRI uses (Schneider and Jejjala 2019). Because brain-state spheres are probably also packed together in a high dimensional lattice, they are unorderable, and this solves the current conundrum. However, they could be compared along particular dimensions such as a sleep-wake axis.

By contrast, one can objectively measure decisions being made in the human brain but that comes down to nerve impulses and then their underlying physics. We do not know how to leap the apparent gap from objective physics to subjectivity. But here is an interesting connection. The opening and closing of gates on nerve membranes are making decisions in the same way that EcoRI makes a decision. They are both molecular machines and follow the definition of molecular machines (Schneider 1991).

So tentatively we can assign decision making not only to humans and cats but also to neurons, membrane gates and EcoRI. Mathematically there is no distinction between these—they all make decisions by selecting hypersphere states in high dimensional noisy spaces. If molecular machines, beings, and neurons all make decisions, could they all be potentially conscious, to varying degrees?

I know what it is like to be conscious, it includes a subjective or egocentric awareness of my surroundings (McBeath et al. 2018). If I were an EcoRI molecule (Farrell 1950; Nagel 1974), my conscousness would be limited to whether I was binding to DNA and whether I was binding to the DNA sequence GAATTC. If the latter were true I would attempt to cut the DNA. Is that satisfying to a molecule? Probably not - there isn't any apparent machinery for a pleasure center as humans and other animals have. But maybe we can say that the 12 bit decision by EcoRI is a 12 bit consciousness.

Decisions and Ethics

Having made this unusual conclusion leads us deeper into philosophy. Buddhists have an imperative to save all sentient beings (Lama 1990) (page 96). Is a smart and inventive cat named Molly-Cule sentient because she decides to go outside 70% of the time? Is an EcoRI protein molecule sentient because it makes selections that can be precisely measured in bits with 70% isothermal efficiency? It is impractical and impossible to save every bacterium, let alone all of its molecular machines (Schneider 1991). Yet perhaps we can at least extend protection, comfort and kindness to as many bit-deciding higher beings as possible, beyond human patients (Mathers 2016; Agarwal et al. 2021) to include insects (Barrett 2026) and even plants (Schlanger 2024; Gagliano et al. 2018) and mycorrhizal fungi who use complex underground brain-like communication networks (Beiler et al. 2010; Boyno et al. 2022). Following this trend in modern science (Webb et al. 2023) should we go further and consider the EcoRI enzyme worthy of protection or at least empathy? Doing so seems seems impractical given that cells are packed with billions of such molecules (Milo 2013). One solution is to have empathy or consideration for higher level or more complex biological objects and allow or hope that that covers the numerous molecular machines. Where to draw the line is open to debate.

The Mathematics of Decisions

To summarize, we have looked at decision processes for a molecule and a Mollycule. Surprisingly, they both express the same isothermal efficiency, around 70%. Isothermal efficiencies are a measure of how the distinct high dimensional spheres that represent biological states are related to each other. The key is an equation that relates the isothermal efficiency to the distance between the hyperspheres:

$$\text{isothermal efficiency} = \frac{\ln(P/N + 1)}{P/N} \quad (1)$$

where P/N is how far apart the spheres are (Schneider 2010a). When $P/N = 1$ we find from this equation that the efficiency is $\ln 2 \approx 0.6931$. Running this equation backwards (using Newton's method) when the isothermal efficiency is near 70%, $P/N = 1$ and the hyperspheres are just kissing (Schneider 2010a). So observing a 70% isothermal efficiency implies that the biological system has evolved to have distinct states.

Reversing this logic again, if we assume that decisions being distinct is the most important evolved property of biological states, then it follows that 70% should often appear in the data, including all forms of life and the decision-making and consciousness of plants. Going further into

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designed and trained human-built intelligent machines, do they also follow these mathematical rules? The isothermal efficiency of a vast number of systems and their appropriate ethical treatment remains to be explored.

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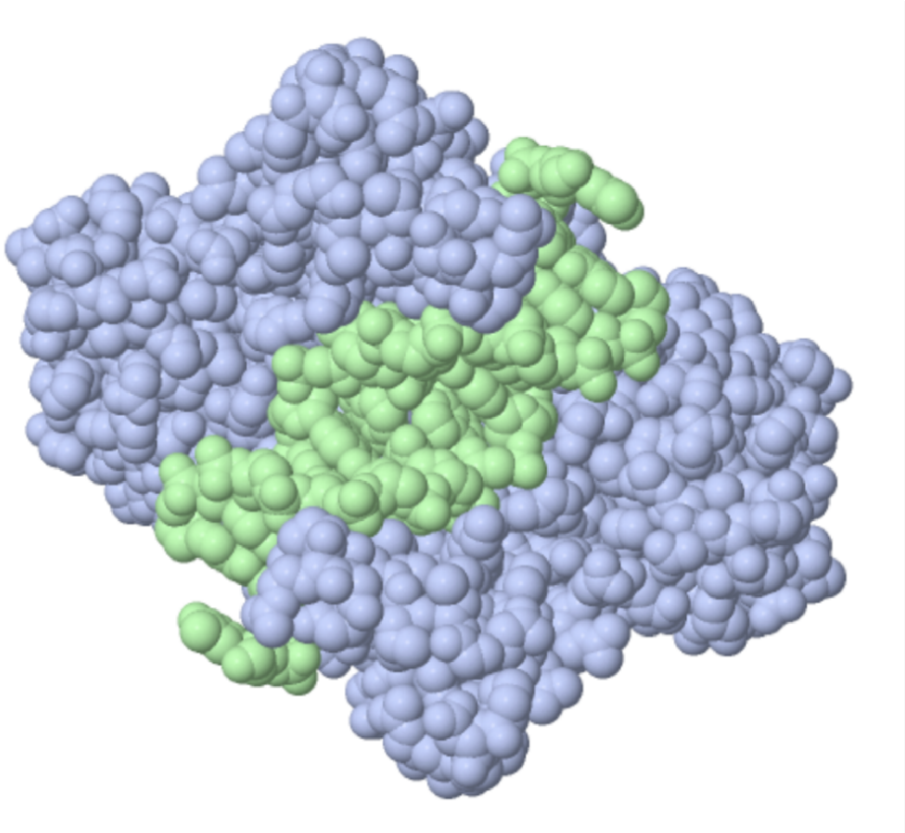
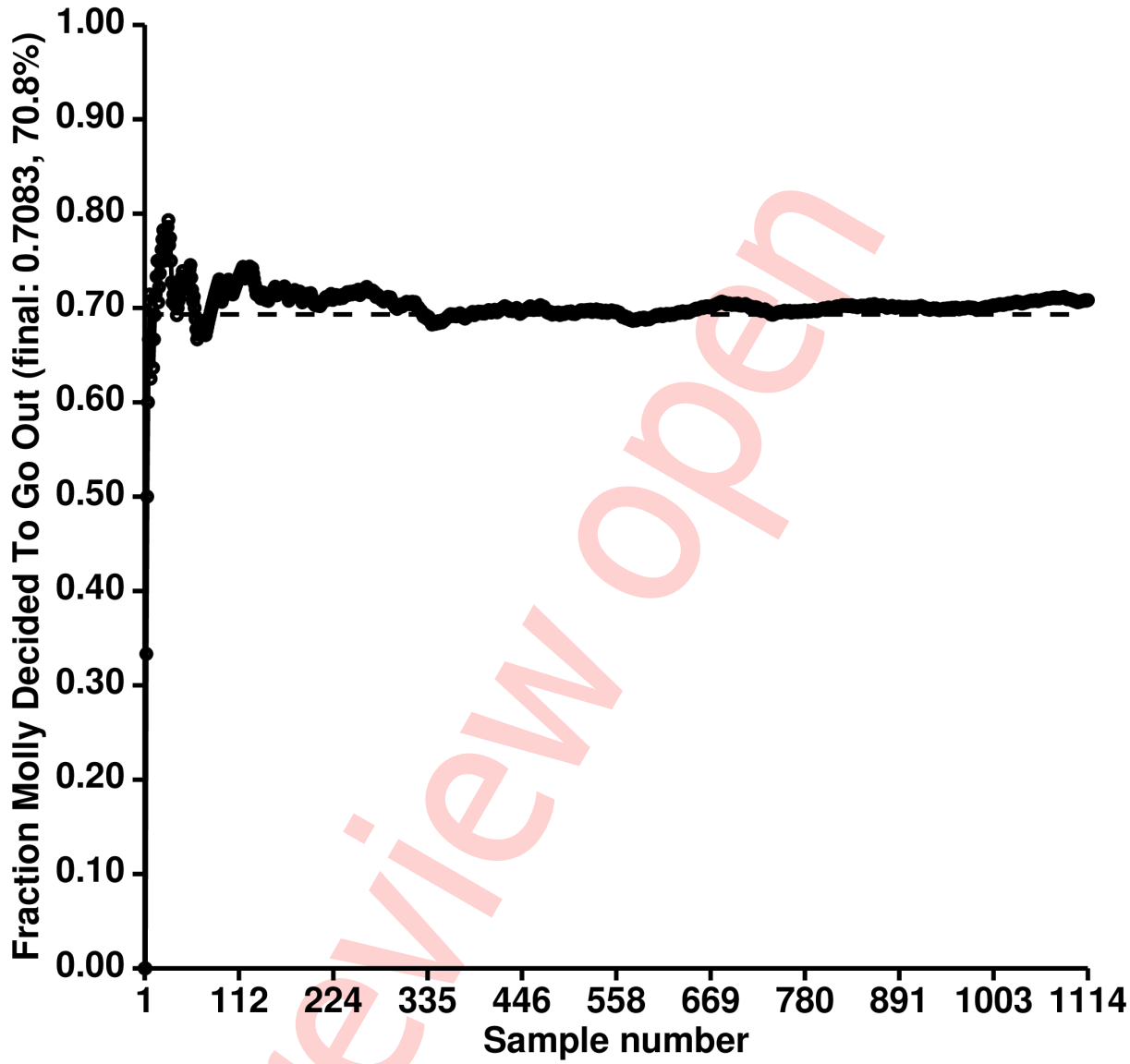


Figure 1: EcoRI protein (light blue) bound to DNA (green). The structure comes from the Protein Data Bank entry 1CKQ by M. Horvath and J. M. Rosenberg using the JSmol (JavaScript) display with the parameters Style: Space Fill, color: By Chain, Surface: None. https://www.rcsb.org/3d-view/jsmol/1CKQ/1. The Google Gemini AI with the prompt "Find the total number of atoms in Protein Database entry 1CKQ for the two protein chains, the two DNA strands and including all hydrogen atoms, but not crystallographic water" gave various results "between 9,100 and 9,250 atoms (with ∼9,200 atoms being the standard baseline depending on the specific protonation states assigned to histidine, glutamate, aspartate, and the terminal ends)."

REVIEW



Figure 2: Collaborative shape art with Molly. I made the groove in the bean bag. Molly filled it with her body and tail. More Molly stories are at https://alum.mit.edu/www/toms/mollystory.html. Fun fact: Molly's tail, surrounded by the beanbag, was about 2 cm across while the diameter of DNA, surrounded by EcoRI in Fig. 1, is about 2 nm, which is 2cm / 2nm = 10 million fold smaller.



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Figure 3: Fraction of the time that Molly decided to go out. The dashed line is $\ln 2 \approx 0.6931$, the theoretical maximum decision efficiency (Schneider 2010a; Schneider 2010b; Schneider 2023). Note on how these data were obtained: when Molly would go to the door, I would open it. I would not urge her to go out or to stay. If she did not go out or go back in, after a few seconds I would close the door. Other than limiting her decision making time, as far as I know I did not influence her choice, so one might expect similar results with an automated door opener. Molly, a short haired female domestic cat received regular veterinary care (Bickell 2023). The recording was from 2019 March 25 to 2020 March 25, unintentionally exactly one year. Recording ended just as the COVID pandemic officially began on 2020 March 11. Temperatures were obtained from www.weather.gov. The mean temperatures between deciding on In (4.8 ± 5.2C, $n = 292$) and Out (6.4 ± 6.1C, $n = 708$) differed significantly by 1.6 ± 8.0 degrees C (Welch's t-test, $p = 2.1 \times 10^{-5}$). This is likely to be one of the dimensions of Molly's decision space. Original count data are in the file molly.csv; missing temperature data are indicated by '='.

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