The Subjective Experience of Time: Welfare Implications

Jason Schukraft

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Executive Summary

The subjective experience of time refers to how slow or fast time appears to pass for an individual. Animals with faster rates of subjective experience undergo more subjective moments per objective unit of time than animals with slower rates of subjective experience. Roughly speaking, animals with faster rates of subjective experience perceive the world as if it were slowed down compared to the perceptions of animals with slower rates of subjective experience. Based on human reports of alterations in the subjective experience of time, as well as general differences in behavior, neurology, and temporal resolution across animals, I estimate there is a ~70% chance that there exist morally relevant differences in the subjective experience of time across species.

Differences in the subjective experience of time would affect the perceived duration of experiences and thus would affect the quality of experiences. An animal's subjective rate of experience determines the number of subjective moments of pain (or pleasure) a painful (or pleasurable) event of a given objective duration generates. Such differences would be relevant to most plausible theories of welfare because most plausible theories of welfare hold that the subjective nature of experience matters morally.

An animal's maximum rate of subjective experience helps determine its capacity for welfare. Animals with faster rates of subjective experience will, all else equal, have a higher capacity for welfare than animals with slower rates of subjective experience. Unlike many other determinants of capacity for welfare, the subjective experience of time is also directly relevant to an animal's realized welfare. The quality of experience is the product of its valence, phenomenal intensity, and subjective rate of experience. For many animals, the phenomenal intensity of experiences varies considerably throughout an individual's lifetime. Subjective rates of experience may be malleable, but for most animals they appear to vary much less frequently than phenomenal intensity. For this reason, even those skeptical of the practical import of capacity for welfare will want to incorporate rates of subjective experience into their welfare measures.

Differences in neurology, reaction times, and temporal integration windows provide means to roughly measure the subjective experience of time across species. Based on 13 relevant metrics I have identified, I estimate that characteristic differences in the subjective experience of time span no more than two orders of magnitude, with humans falling approximately midway on the spectrum. Arranging animals on this spectrum is likely to produce a radically different ordinal ranking than arranging animals according to neuron count, encephalization quotient, brain-mass-to-body-mass ratio, or other metrics related to brain size. Incorporating considerations about the subjective experience of time into our interspecies comparisons (currently dominated by brain size considerations) would likely change the way we prioritize animals.

Although much uncertainty remains, it appears many animals have rates of subjective experience faster than that of humans. For example, convergent evidence from their neurology, behavior, and the temporal resolution of their senses indicates songbirds and honeybees experience 2-10 times as many subjective moments per objective unit of time as humans. Thus, all else equal, the painful experiences of animals like songbirds and honey bees likely generate more suffering per objective unit of time than comparable animals with slower rates of subjective experience. Incorporating this sort of information into our prioritization decisions may allow us to improve the efficiency with which we distribute resources across different groups of animals.

Introduction and Context

This post is the third in [Rethink Priorities](#)' series exploring comparative moral value across species. The primary goal of this series is to improve the way resources are allocated within the effective animal advocacy movement. A secondary goal is to improve the allocation of resources between human-focused cause areas and nonhuman-animal-focused cause areas. In the [first post](#) I lay the conceptual framework for the rest of the series, outlining different theories of welfare and moral status and the relationship between the two. In the [second post](#), I present and evaluate two methodological schema for measuring and comparing capacity for welfare and moral status. In this, the third entry in the series, I explain what the subjective experience of time is, why it matters, and why it's plausible that there are morally significant differences in the subjective experience of time across species. In the next entry in the series, I explore critical flicker-fusion frequency as a potential proxy for the subjective experience of time. In the following batch of posts, I investigate variation in the characteristic range of intensity of valenced experience across species.

The Metric Problem

In the [second post](#) in this series, I discussed ways to measure moral status and capacity for welfare across different types of animals. To make comparative judgments concerning moral status or capacity for welfare, we must find empirically measurable proxies for the characteristics that matter morally. And it must be possible to compare these proxies across a wide array of species.

The animal kingdom encompasses a vast and diverse range of animals that plausibly have moral standing.[1] Humans directly exploit many of these animals: pigs, cows, goats, sheep, rabbits, rats, chickens, turkeys, ducks, geese, frogs, turtles, herring, anchovies, carp, tilapia, cod, catfish, eels, octopuses, squid, shrimp, bees, silkworms, snails, and many others.[2] An even greater variety of animals plausibly suffer in the wild (independent of human action), and the welfare of these animals matters too. To fully judge interventions and policies, we need to be able to evaluate welfare gains and losses across many species.[3] To produce such comparisons, we need to know how many animals are affected, how their conditions are changed by the proposed intervention or policy, and how those condition changes translate into welfare changes. To understand how condition changes translate into welfare changes, it's helpful to know about differences in [capacity for welfare](#), which is how well or poorly an animal's life can go. If an animal's welfare can only vacillate between mild endpoints, then big differences in conditions won't translate into big differences in welfare. If an animal's welfare can vacillate between extreme endpoints, big differences in conditions could translate into big differences in welfare.[4] And if animals differ in [moral status](#), then we will also want to weight welfare changes by moral status so as to compare interventions and policies by their effects on [status-adjusted welfare](#).

Such comparisons require some way to assess moral status and capacity for welfare. A metric to assess moral status or capacity for welfare would ideally meet a variety of desiderata. The metric must be *valid*—that is, it must actually track one or more morally salient characteristics that contribute to capacity for welfare or moral status. The metric must be *accurate*—that is, it must be sensitive to differences in capacity for welfare or moral status. The metric ought to be *applicable across species*—that is, it ought to be accurate and valid with respect to phylogenetically distant animals occupying different ecological niches. Finally, the metric must be *practically measurable*—that is, it must be feasible (now or in the near future) to collect actual data for a wide variety of species.[5]

Below I present the subjective experience of time as an example of a morally relevant feature that can potentially be operationalized in a way that appears to satisfy those four desiderata. Of course, the various ways to operationalize the subject experience of time are not perfect. And naturally, the metrics I propose do not give anything like a full picture of capacity for welfare or moral status. At best, they deliver a glimpse at one factor that plausibly contributes to moral status and/or capacity for welfare. In the ideal case, we would want to identify and compare multiple such metrics to see where recommendations converge and to test how sensitive our decision-making is to choice of metric. A full analysis of capacity for welfare or moral status would identify dozens of morally

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1 See Rethink Priorities' [Invertebrate Sentience Table](#) (and related documents) for an overview of the evidence of sentience in a variety of animals. As I discuss in the [first post](#) in this series, sentience is generally thought to be sufficient for moral standing.

2 Through habitat destruction, environmental degradation, and anthropogenic climate change, humans indirectly affect almost all animals on the planet.

3 Presumably not all animals are welfare subjects. It's contentious where to draw the line between animals that are welfare subjects and animals that are not welfare subjects. Even if one adopted a conservative framework according to which only mammals are welfare subjects, the interspecies comparison problem would remain (though it would be more tractable).

4 In either case, the endpoints need not be symmetric between positive welfare and negative welfare.

5 This list is adapted from [Browning 2020](#). Her focus is on measuring *realized* welfare, but I think the desiderata apply equally well to measuring capacity for welfare and moral status.

relevant features, each with multiple operationalizations.[6]

Nonetheless, the subjective experience of time is useful to investigate for several reasons. First, the subjective experience of time is directly relevant to *realized* welfare as well as capacity for welfare, so even those who are skeptical of the practical import of capacity for welfare will want to account for differences in the subjective experience of time. Second, the subjective experience of time is relatively neglected as a potential metric of comparative moral value. The most commonly used metric for comparisons of moral value across species is neuron count (or some variant thereof).[7] As we'll see below, many of the potential proxies for the subjective experience of time generate a radically different ordinal ranking of animals compared to the ranking generated using neuron counts. We don't know which general feature is more important, but proxies for the subjective experience of time are not obviously much worse than neuron count at accurately tracking salient moral characteristics,[8] so the fact that using these metrics generates a radically different ranking is significant for two reasons. First, it gives us additional data points to consider. If we incorporate various time experience metrics into our reasoning (perhaps weighting them equally with various brain size metrics), we would change the way we rank animals. Second, unlike the ranking generated by neuron count, the rankings generated by time experience metrics don't accord with our pre-theoretic intuitions about comparative moral value. This is a helpful reminder about how little we know about comparative moral value (and possibly about the danger of speciesist prejudices creeping into our rankings). We should try to incorporate this uncertainty into our decision-making process.

The Subjective Experience of Time

In simple terms, the subjective experience of time is how fast time appears to pass from the viewpoint of a particular individual.[9] Its contrast is *objective time* (sometimes called *physical time* in the literature), which, holding the reference frame fixed, always passes at the same rate and never differs among individuals.[10] The subjective experience of time refers to the felt duration of events. Two observers can agree on the objective length of an event but disagree on its felt duration. Other things equal, the faster one's rate of subjective experience, the more thoughts and sensations one can experience in a given unit of objective time. To conceptualize differences in the subjective experience of time, one can imagine a movie either slowed down or sped up. The faster one's rate of subjective experience, the more the world will resemble a movie played in slow-motion; the slower one's rate of subjective experience, the more the world will resemble a movie in fast-forward.[11]

It's possible that the subjective experience of time invariably tracks objective time and hence that time appears to pass at the same rate for all individuals. In that case, *subjective experience of time* would not be a useful concept. And because the subjective experience of time is a feature of internal experience, we cannot measure it directly and thus cannot be certain whether or not it varies among animals (especially nonhuman animals who cannot offer self-reports). In this way, the subjective experience of time is no different than any other aspect of phenomenal experience, such as the perception of pain. However, the fact that we cannot measure internal experiences directly does not entail that we cannot sometimes justifiably infer their existence. We can use inference to the best explanation to justifiably conclude that some nonhuman animals feel pain.[12] Similarly, we can in principle use inference to the best explanation to justifiably conclude that some animals differ with respect to their subjective experience of time. As we'll

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6   The metrics would also be weighted by plausibility and importance and then combined.

7   See, for example, Budolfson & Spears 2019.

8   In some ways, the time experience metrics are much better. It's clearer what these metrics purport to track and clearer why what they purport to track is morally relevant. (See the section "Why the Subjective Experience of Time Matters.") In contrast, it's not clear exactly what neuron counts are supposed to track. If they are meant to track something like intensity of experience, then it's not clear whether the correlation is positive or negative. If they are meant to track something like cognitive sophistication, then it's not clear that cognitive sophistication is more important than the subjective experience of time.

9   Some philosophers dispute the claim that time appears to pass. Here I aim to employ the phrase only in its everyday, theoretically unproblematic sense. To be clear, the passage of time is not the sort of thing that is directly perceived; rather there is a temporal aspect to the detection of change in every sensory modality. Time appears to slow down when one is subject to more experiences per objective unit of time; it appears to speed up when one is subject to fewer experiences per objective unit of time.

10 Relativistic physics makes the notion *objective* time somewhat problematic. Those difficulties, however, are orthogonal to the issue at hand. Accelerating a creature to a significant fraction of the speed of light shifts its reference frame with respect to non-accelerated creatures such that the creatures may not agree on which events are simultaneous. But it doesn't alter the creature's subjective experience of time.

11 However, it's important to remember that this is only a metaphor. Visual perception is importantly disanalogous to mechanical recording devices. As Holcombe 2009 notes, "Video cameras have a single temporal limit set by the frame rate. The human visual system has multiple temporal limits set by its various constituent mechanisms" (216).

12 We can at least use inference to the best explanation to infer that other *humans* feel pain. Rejecting this inference pushes one dangerously close to solipsism.

see below, there is indeed modest evidence that suggests that the subjective experience of time characteristically differs among species.[13]

It's important to distinguish *veridical* differences in the subjective experience of time from *illusory* differences in the subjective experience of time. We're familiar with illusory distortions of the passage of time from everyday examples. Some days fly by; others crawl. Waiting and boredom seem to slow time down; enjoyable activity appears to speed time up. This is undoubtedly a real

phenomenon, but we need not appeal to differences in the subjective experience of time in order to explain the psychology of these perceived distortions.[14] In fact, appealing to differences in the subjective experience of time appears to be a rather poor explanation.[15] After all, it's not as if on the days that time crawls that people appear to be moving in slow motion or that the tempo of one's favorite song is slowed.[16] (However, there *are* certain 'fight-or-flight' events that *do* appear to slow time down—this class of events is discussed in more detail below.)

The key difference between veridical differences in the subjective experience of time and illusory differences in the subjective experience of time is that veridical differences affect the moral value of events and illusory differences do not. Veridical differences are always *experiential*: the number of subjective moments one experiences per objective unit of time has changed. Illusory differences are often (though not exclusively) *memorial*: one retrospectively remembers an event as longer or shorter than it actually was. To judge whether some phenomenon constitutes a veridical or illusory difference in the subjective experience of time, it's helpful to ask whether the phenomenon is morally relevant to the event. All else equal, increasing the subjective duration of a pleasurable event increases the amount of experienced pleasure. Increasing

the retrospectively recollected duration of an event does not increase the amount of experienced pleasure.[17] (See Appendix 1 for more discussion of the distinction between temporal *experience* and temporal *judgment*.)

The subjective experience of time is *subjective* in the sense that it is relative to some perceiver. However, the subjectivity of the phenomenon ought not impugn its genuineness. If it's true that rates of subjective experience vary, then it is an *objective* fact that animals with faster rates of subjective experience undergo subjectively longer experiences per unit of objective time. For two otherwise similar individuals who differ in their subjective experience of time, the individual with the faster rate of subjective experience can (in principle) think more thoughts and feel more sensations than the individual with the slower rate of subjective experience. The perception of pain is subjective in the same way. Two subjects might be exposed to a negative stimulus (an electric shock, say) of the same intensity but differ with respect to the felt badness of the subsequent pain. Such a difference is subjective (in that the painfulness of the shock is relative to the subject being shocked) but no less genuine in virtue of the subjectivity. What matters morally is not the objective intensity of the stimulus, but the subjective badness of the experience.

As we'll see below, there are conditions under which it is plausible (though not certain) that an individual's subjective experience of time changes. Humans who have ingested certain mind-altering drugs sometimes report distortions in their experience of time. Humans who have experienced intensely surprising, frightening, and life-threatening events often report that time seemed to slow down until the danger passed. These sorts of events may also induce changes in the subjective experience of time in nonhuman animals. However, for the purposes of comparing species, it's useful to focus on an animal's *characteristic* experience of time, by which I mean the species-typical resting experience of time.

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13 There is also some evidence that the subjective experience of time varies slightly among individuals within a species, though this variation may be so slight that its moral importance is negligible. Additionally, there is evidence that certain events can trigger temporary changes in the subjective experience of time. The moral significance of these events (which appear to be common in some species and rare in others) is as yet unknown.

14 In one study (Watt 1991), bored subjects reported that the time passed slowly when engaged in a tedious number-circling activity, but they were no better or worse at estimating the actual duration of the activity than non-bored subjects. A later study (Danckert & Allman 2005) found that boredom-*prone* individuals were more likely to overestimate the passage of time. However in this study there was no correlation between being more or less boredom-prone (as scored by the Boredom Proneness Scale) and *actually reporting that the activity was more or less boring.* (Basically everybody thought it was super boring.) The authors are careful to note that "the differences we observed in temporal perception were due to robust differences in *trait* susceptibility to boredom" and that "it would appear that state feelings of boredom did not influence our results" (243).

15 Ian Phillips appeals to an analogy with illusory spatial perception: "we can agree that when viewed at an angle a circular coin *looks* elliptical without thinking that we misperceive the coin as elliptical" (Phillips 2013: 240). We need not posit an elliptical object to explain why the coin looks elliptical. Similarly, although a day of boredom seems to drag on for longer than a day of excitement, we need not posit actual differences in the rate of subjective experience to explain the temporal illusion.

16 See Sten Nadolny's novel *The Discovery of Slowness* for the fictional story of a person with a slowed rate of subjective experience. As a result, the world appears very fast to him and his reactions appear very slow to others.

17 Of course, remembering a pleasurable event as longer than it actually was might increase one's pleasure of actively recalling the event. But the increase in pleasure comes from one's present recollection, not the past event.

Why the Subjective Experience of Time Matters

In the first post in this series, I outlined three broad families of theories of welfare: (1) hedonistic theories, according to which welfare is the balance of experienced pleasure and pain, (2) desire-fulfillment theories, according to which welfare is the degree to which one's desires are satisfied, and (3) objective list theories, according to which welfare is the extent to which one attains non-instrumental goods like happiness, virtue, wisdom, friendship, knowledge, and love. The subjective experience of time is a fundamental aspect of experience, and according to each of these families of theories, the quality of experience is morally significant.

An animal's subjective experience of time refers to the phenomenal duration of its experiences. The phenomenal quality of an experience is the product of its valenced intensity (either positive or negative) and its duration. We know that the valenced intensity of a stimulus is subject-relative. There is not a unique answer to the question 'How painful (pleasurable) is this stimulus?' The answer depends on the perception of the subject.[18] It's possible that the phenomenal duration of a stimulus is subject-relative in a similar way. If animals differ with respect to the subjective experience of time, then there is no unique answer to the question 'How long did this stimulus appear to last?'

We could insist on calculating the quality of an experience by multiplying its subject-relative intensity by its subject-invariant duration (as measured by objective time). But if it is the *perceived* intensity of a stimulus that matters morally, rather than any objective feature of the stimulus, it's unclear why we shouldn't apply the same reasoning to duration. It seems intuitively clear that a stimulus that feels more painful on one occasion is worse than a stimulus that feels less painful on another occasion, even if the objective magnitude of the stimuli is the same in both cases. If that's right, then it seems intuitively equally plausible that a painful event that feels longer in some robust sense[19] is worse than a

similar event that feels shorter, even if the objective duration of the two events is the same.

If two animals experience time differently, then a pain of the same phenomenal intensity experienced for the same objective duration would not in general generate the same amount of suffering. The animal with the faster subjective experiences would suffer more because it would feel the pain longer. Hence, we should not naively equate the phenomenal extension of pain with its duration expressed in objective time. The true quality of an experience is the product of its phenomenal intensity and phenomenal extension.

The claim here is that the quality of an experience is the product of its felt valenced intensity and its felt duration. Felt duration is distinct from *estimated* duration. Estimated duration, like estimated intensity, is retrospective. As we'll see below, there are many conditions under which our estimated durations are systematically skewed in ways that don't reflect our felt duration. Similarly, there are conditions under which our retrospective estimates of painfulness and pleasurableness are systematically mistaken in ways that don't reflect our felt experience.[20] But what matters morally is not retrospective estimates of pain, but experienced pain.[21] When someone with short-term memory loss stubs her toe, the badness of the experience isn't erased because no memory of the experience forms. Our retrospective perceptions of our experiences are important, but the moral value of an experience doesn't change when our memories of the experience change. (See Appendix 1 for more discussion of the distinction between temporal *experience* and temporal *judgment*.)

According to hedonism, experiences are all that ultimately matter morally. Although other theories of welfare deny that experiences are *all* that matter, no plausible theory of welfare denies that experiences *do* matter in some respect. Experiences are relevant to desire-fulfillment accounts of welfare. We generally desire pleasurable experiences and desire to avoid painful experiences. (And painful experiences often get in the way of our non-experiential

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18   The subject's perceptions may vary in predictable ways, but the existence of such psycho-physical laws does not change the fact that it is the subject's internal feelings that ground the valence and intensity of the experience, not any external property of the stimulus.

19   The relevant sense of 'longer' is that the creature experiencing the 'longer' event undergoes more subjective moments of pain than the creature experiencing the 'shorter' event.

20   See Kahneman 2011: 378-381 for a discussion of the peak-end rule of pain and duration neglect in memory, which nicely illustrate that "[c]onfusing experience with the memory of it is a compelling cognitive illusion" (381).

21   There are, of course, many reasons to be attentive to systematic variations in people's retrospective estimates of pain. Suppose there is some useful medical operation that is beneficial but also reputed to be painful. If the goal is to reduce how painful patients report the procedure to be (and thus hopefully increase the number of patients who get the operation), it would be more helpful to reduce the peak-intensity of pain during the operation than to reduce the duration of the procedure. See footnote 20.

desires.[22]) Objective list theories maintain that there are a variety of intrinsic goods, but all plausible objective list theories include goods either constituted by our experiences (such as pleasure) or for which our experiences are directly relevant (such as life satisfaction or happiness). So hedonistic theories, desire-fulfillment theories, and objective list theories all agree that experiences contribute to welfare. Since differences in the subjective experience of time alter the value of experiences, such differences contribute to capacity for welfare. All else equal, animals with faster rates of subjective experience will have a greater capacity for welfare than animals with slower rates of subjective experience.

The subjective experience of time is also directly relevant to realized welfare. Some factors influence capacity for welfare by extending one's intensity range of possible experiences, without necessarily influencing the intensity of one's *actual* experiences. (A human, with our vast intellectual and emotional sophistication, may be capable of towering heights of happiness and steep valleys of despair. Nonetheless, a given human might only vacillate between very mild happiness and suffering.) The subjective experience of time is not like that. Rather than merely extending the intensity range of possible experiences, differences in the subjective experience of time act as multipliers (either greater or less than one) on all actual experiences. Even if we were uncertain about most of the factors that contribute to capacity for welfare (or skeptical of the importance of capacity for welfare considerations), we could still use proxies for the subjective experience time to help us compare interventions that target different species. For a given condition that causes suffering, animals with a faster rate of subjective experience will, all else equal, suffer more than animals with a slower rate of subjective experience.

It's less certain that the subjective experience of time is relevant to moral status. On some views of moral status, capacity for welfare plays a role in determining moral status. Since the subjective experience of time contributes to capacity for welfare, on views according to which capacity for welfare and moral status are tightly linked, the subjective experience of time will be relevant to moral status by virtue of its connection to capacity for welfare. However, for views according to which capacity for welfare is independent of moral status, the relevance of the subjective experience of time to moral status is less clear. It doesn't appear as if the subjective experience of time is related in any interesting way to self-awareness, autonomy, emotional complexity, normative thought, sociability or many of the other characteristics that plausibly determine moral status.

The General Case for Differences in the Subjective Experience of Time

There's no point searching for a metric that tracks characteristic differences in the subjective experience of time across species unless there's reason to think there **are** characteristic differences in the subjective experience of time across species. Certainly, there's no **guarantee** that such differences exist. However, for the reasons outlined below, I think it's plausible that such differences do exist. I currently estimate there is a ~70% chance that there exist characteristic and significant differences in the subjective experience of time across different types of animals. (I operationalize 'characteristic and significant differences in the subjective experience of time' as the claim that for at least half their daily waking lives, some animals maintain subjective rates of experience at least twice as fast as some other animals.) Given another hundred hours of research, I don't think my credence would change by more than ten percentage points in either direction. However, new empirical evidence, most of which is obtainable with current technology and which could be feasibly generated within a decade (given the right financial incentives), could plausibly push my credence below 50% or above 90%.

Morphological, Behavioral, and Neurological Differences

First, we know that animals differ with respect to their perceptual experience. Consider the many sensory modalities that some animals have that others lack: "Some fish emit electric discharges and then use electric sense organs to detect distortions of the electric field produced by nearby objects. Some beetles and snakes use heat-sensitive sense organs to detect sources of heat. Several animals navigate by the stars or by polarized sunlight. It seems that animals in several phyla navigate by detecting the Earth's magnetic field" ([Howard 2012](#)). Moreover, animals often exploit the same general modalities in different ways. Some animals rely primarily on scotopic rather than photopic vision;[23] bats and some marine mammals use audition to navigate (echo-location); dogs utilize olfaction much differently than humans. Since the perceptual experience of animals varies so widely, it may ap-

termine moral status.

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22 Non-experiential desires are desires for objective changes in reality independent of our experience of those changes. Pleasurable experiences (e.g., the pleasure of eating ice cream) can also derail the pursuit of our non-experiential goals.

23 Photopic vision is generally employed in well-lit conditions, while scotopic vision is generally employed in low-light conditions. In many animals, photopic vision enables color perception while scotopic vision does not. In humans, photopic vision is mediated by cone cells in the eyes, while scotopic vision is mediated by rod cells in the eyes.

pear prima facie surprising if temporal experience were uniform across animals.

Even before considering any experimental evidence, given what we know about differences in behavior, morphology, and

neurology across species, it would be hugely surprising if there weren't characteristic differences in, say, vision, audition, or olfaction. If time perception is at all like visual, auditory, or olfactory perception, we should also expect characteristic temporal differences across species. However, I think there's good reason to believe that time perception is *not* at all like visual, auditory, or olfactory perception. Indeed, time *perception* probably isn't even perception, strictly speaking. The term *time perception* is a bit of a misnomer. The mechanisms that allegedly influence the subjective experience of time are not meant to constitute some novel sensory modality. Time itself is not the sort of thing that is amenable to direct perception. Rather, there is a temporal dimension to every sort of perceiving. What we actually observe are changes or events *in* time.[24] So if general morphological, behavioral, and neurological differences across species increase one's credence in characteristic differences in temporal experience across species, they shouldn't increase one's credence by much.

Human Reports of Changes in the Subjective Experience of Time

Second, under certain conditions, humans often report differences in their own subjective experience of time. For instance, people frequently claim that during frightening events, such as automobile accidents or combat in warfare, time seems to slow down.[25,26] Humans also sometimes report that mind-altering drugs modify one's subjective experience of time. Regarding these reports, there are two possibilities. One is that such reports are literally true: the subjective experience of time really does change in some robust, genuine way. The other possibility is that such reports are illusory: frightening events and psychedelic drugs heighten the senses, producing much more vivid, fine-grained memories which

upon recollection give us the mistaken impression that we experienced the world at a different pace.[27] I'll discuss the two possibilities in turn.

Some authors urge us to take reports of differences in the subjective experience of time literally. Valtteri Arstila writes, "When people are suddenly faced with situations that they perceive as threatening, later they often report having had experiences with unusual phenomenology. I argue here that the phenomenology should be taken as given and reported in its entirety. This is because otherwise some of the most relevant phenomena in these situations—such as how people can act in unusually fast and purposeful ways to save their lives—would be left unaddressed" (Arstila 2012: 8). The exact mechanism(s) that allegedly produces this phenomenon is unclear. The general idea is that the extreme stress of the situation alters one's brain such that "(1) our senses record data at higher density; (2) our brains sample more of these data; [or] (3) our brains process these sampled data faster" (Buckley 2014: 1). According to Ian Phillips, the world appears to slow down during traumatic experiences because we have many more thoughts per unit of time than we normally do. "According to this hypothesis, what subjects are reporting in terms of 'time slowing down' are experiences in which an unusually large amount of non-perceptual mental activity occurs within a certain objective period: much more activity than would normally occur during such a period" (Phillips 2013: 233).[28] (See Appendix 2 for more discussion of theoretical models of temporal representation.)

If differences in the subjective experience of time are possible across moments, there is probably an evolutionary account of the phenomenon that explains why changes in the perceived passage of time are beneficial. (For instance, in life-or-death situations, individuals with faster rates of subjective experience have more subjective time to react than individuals with slower rates of subjective experience; it's plausible that individuals with faster rates of subjective experience tend to survive such situations more often than individuals with slower rates of subjective experience.) If humans can experience differences in the subjective experience of time, it appears quite likely that nonhuman animals would be

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24   For more on the philosophical difficulties related to the 'perception' of time, see this entry in the *Stanford Encyclopedia of Philosophy*.

25   "Car crash victims, pilots forced to eject from their planes, rock climbers suffering serious falls, and other survivors of life-threatening danger, reliably report that the traumatic events which they experienced appeared to last much longer than events of the same objective length in normal conditions" (Phillips 2013: 228). See footnote 4 in Phillips 2013 for citations to support this claim.

26   It's important not to overstate the phenomenon. Hancock & Weaver 2005 report on an unpublished survey of fighter pilots who had ejected from their aircraft, a paradigmatically intense experience (Fair 1984). Of the 28 surveyed pilots, only 15 reported an apparent slowing of the passage of time.

27   "Since it is ethically unjustifiable to create an experimental setting that is dangerous, it remains unclear whether people in such situations really experience slow motion, or whether—after the event, and on the basis of the emotional charge of what they have gone through—they simply believe that they felt everything happening more slowly" (Wittman 2016: 35).

28   Although Phillips concedes that "our experiences of duration in trauma are not strictly speaking illusions" (236), he appears to be intending to offer a deflationary account of the phenomenon, though admittedly the distinction between a reifying explanation and a deflationary explanation is blurry in this case.

able to experience such differences as well. It's hard to come up with a plausible reason that the phenomenon would be restricted to humans. And if individual animals experience time differently depending on the situation, it seems plausible that there would be characteristic differences in the subjective experience of time across species. Physiology differs fairly radically among animals, and different animals inhabit different ecological niches, which may optimize for different rates of subjective experience. Differences in the speed of predators and/or prey could exert differential selection pressures leading to differences in the subjective experience of time.

On the other hand, some authors caution against interpreting anecdotal reports of time slowing down literally. Chess Stetson, Matthew Fiesta, and David Eagleman argue that "at this stage there is no evidence to support the hypothesis that subjective time as a whole runs in slow motion during frightening events. Rather, we speculate that the involvement of the amygdala in emotional memory may lead to dilated duration judgments retrospectively, due to a richer, and perhaps secondary encoding of the memories. Upon later readout, such highly salient events may be erroneously interpreted to have spanned a greater period of time" (Stetson, Fiesta, & Eagleman 2007: 3). The basic idea is that during stressful events "our memories store data at higher density" (Buckley 2014: 1) and upon recollection this difference in density induces a memorial illusion of time slowing down. (See Figure 1.) Dan Zakay reports experimental support for this position: "Retrospective duration judgment is a function of the amount of retrieved contextual changes. The more contextual

changes are retrieved, the longer the duration is judged to be. As a result, when information processing during an interval is complex (i.e., remembering a complex geometrical figure), the interval is judged to be longer in retrospect than a respective interval in which information processing was simple (i.e., remembering a simple geometrical figure like a circle). This is because complex information processing is causing more contextual changes to be encoded than simple information processing" (Zakay 2014: 1).

However, even if the perceived slowdown is illusory (merely the product of more vivid memory, say), the phenomenon still demonstrates the conceptual possibility of differences in the subjective experience of time.[29] Once the conceptual possibility of the phenomenon is made salient, we can perhaps more easily look for evidence of the phenomenon among nonhuman animals.

Differences in Reaction Times

The third, oft-cited, reason to think animals differ in their characteristic experience of time is variation in reaction times.[30] Some animals, such as hummingbirds and houseflies, seem to react to the world much more quickly than others. If some of those reactions are under conscious control, then it's plausible that the faster reactions demand a faster rate of subjective experience.[31]

In general, reaction time is negatively correlated with body size.[32] One study found that the smallest terrestrial mammals react about 17 times faster than the largest terrestrial mammals
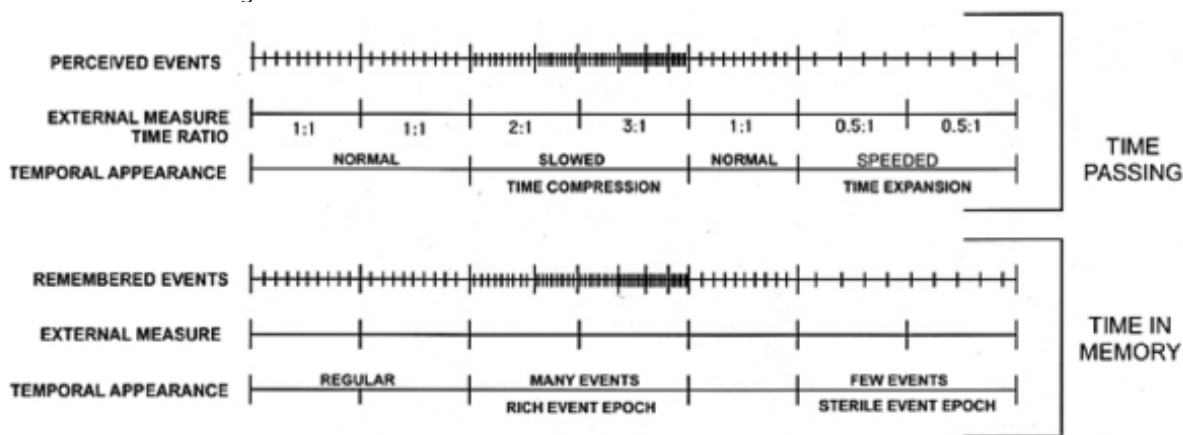

Figure 1: Increases in the data density of stored memories induce the illusion of time slowdown (source: Hancock & Weaver 2005: 201)

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29 The conceptual possibility of differences in the subjective experience of time has been dramatized in a number of formats. For example, see Sten Nadolny's novel *The Discovery of Slowness* for a character with slowed subjective experience. See the *Black Mirror* episode "White Christmas" for characters with dramatically accelerated subjective experience.

30 For example, see Luke Muehlhauser's comments here and Brian Tomasik's comments here.

31 For instance, perhaps it's hard to swat a fly because the fly perceives your hand as if it were moving in slow-motion.

32 Smaller muscles are faster to move, which contributes to faster reaction times.

(More & Donelan 2018). Startle reflexes can be incredibly fast in small insects, as low as 5 ms in some flies (Sourakov 2011: 367). That's much faster than the 30-50 ms it takes a typical human to blink when a puff of air is blown on her eye (Sourakov 2009: 653). Some squid can execute a jet-propelled escape reaction in as little as 50-75 ms (Otis & Gilly 1990: 2912). The star-nosed mole has a tactile reflex time of just 120 ms (Catania & Remple 2004: 519), 20% to 40% faster than humans.

However, it's plausible that many of those impressively fast reactions operate below the level of conscious perception. As an example, think about how quickly a human can pull back her hand from a burning stove. Since the reaction is mediated by the spinal cord, it happens before the conscious sensation of pain is produced. In general, fast knee-jerk-type reflexes, such as startle and stretch reflexes, don't provide evidence for fast subjective experience. And flight control reflexes operate much below conscious experience, so hummingbird and housefly flight stabilization, while impressive, doesn't tell us much about the subjective experience of time. Moreover, although small animals have much faster absolute reaction times than large animals, this advantage is mostly offset by differences in movement rate. Heather More and Maxwell Donelan note that "despite a 1-million-fold range in mass, a 100-fold change in leg length and a more than 15-fold difference in absolute delay, relative delays in the largest terrestrial mammals are only double the duration of those in the smallest" (More & Donelan 2018: 4).

All told, I think differences in reaction time provide evidence for differences in the subjective experience of time, but the strength of the evidence is rather modest.

Differences in Temporal Resolution

Differences in temporal resolution across species offer a fourth reason to think animals differ with respect to their subjective experience of time. Temporal resolution is a measure of the rate at which a perceptual system samples information from its environment. In animals it is best studied in the visual and auditory domains, though in principle the temporal resolution of other sense modalities could be measured. One common measure of visual temporal resolution is critical flicker-fusion frequency (CFF). CFF is "the threshold at which an animal ceases to perceive a flickering light source as a series of flashes, but rather as a continuous

stream of light" (Inger et al. 2014: 2). This threshold characteristically varies across species (and, to a milder extent, across individuals of the same species). CFF is measured as a frequency and expressed in hertz (Hz). Higher values represent better temporal resolution.

If CFF does track the subjective experience of time, it only does so for a subset of animals. It's important to remember that CFF is a *visual* measure. As such, it is inevitably biased against creatures that inhabit low-light environments, like nocturnal or benthic animals[33] (Inger et al. 2014: 2).[34] It is also biased against creatures that primarily rely on other senses like audition (e.g., bats), olfaction (e.g., guinea pigs), and whisking (e.g., rats). The lower CFF thresholds for these animals probably do not give us evidence that their rates of subjective experience are correspondingly lower. Whatever evolutionary advantage a faster rate of subjective experience confers, it seems like that advantage would generally accrue across most sensory modalities, rather than being restricted to vision. (For instance, all else equal, echo-locating bats with better temporal resolution would be better predators than conspecifics with worse temporal resolution.) The existence of fast-moving, highly maneuverable nocturnal and benthic animals give us prima facie reason to think that differences in the subjective experience of time won't be wholly captured by visual measures such as CFF.

CFF values vary considerably across the animal kingdom, though most studied animals are within an order of magnitude of each other. As a reference point, humans are generally reckoned to have a CFF of around 60 Hz. About two-thirds of animals that have been studied have CFF thresholds lower than humans.[35] For instance, the European eel (*Anguilla anguilla*) has a CFF of 14 Hz (Healey et al. 2013), the Sergestid shrimp (*Sergia filictum*) has a CFF of 24 Hz (Frank 2000), the common cuttlefish (*Sepia officinalis*) has a CFF of 42 Hz (Nelson 2003), and the American crayfish (*Cambarus spp*) has a CFF of 53 Hz (Inger et al. 2014). About one-third of studied animals have CFF values higher than humans. For instance, the common octopus (*Octopus vulgaris*) has a CFF of 72 Hz (Hamasaki 1968), the domestic chicken (*Gallus gallus domesticus*) has a CFF of 87 Hz (Healey et al. 2013), and the Tsetse fly (*Glossina morsitans*) has a CFF of 145 Hz (Inger et al. 2014).

The idea that critical flicker-fusion frequency is correlated with characteristic differences in the subjective experience of time

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33 Benthic animals are animals that occupy the lowest level of a body of water. In deep waters, the benthic zone receives little sunlight.

34 "It has been known for some time that animals adapted for low light environments tend to have lower CFFs than animals found in more intense light environments" (Inger et al. 2014: 2).

35 Note that this fact does not entail that two-thirds of all species have CFF values lower than humans. The animals that have been studied thus far are not representative of wider taxa.

across species appears to be taken seriously in the scientific community. For instance, Bartosz Jura of the Nalecz Institute of Biocybernetics and Biomedical Engineering, has explored the connection between CFF and subjective time experience. He writes, "As the values of CFF display a specific species-varied pattern that can be attributed to evolutionary-ecological processes, suggesting that the persistence of visual percepts is precisely tuned in particular species, it seems reasonable to assume that the persistence of other types of contents of conscious experience will also be shaped evolutionarily, in accord with the visual system's CFF, so that they last as long as it is suitable for individuals from species living in given circumstances, not too long and not too short, likely being proportional to intervals separating behaviorally relevant events in which a corresponding type of information is processed" (Jura 2020: 3). Jura concludes, "Subjective time flows with variable rate, as we know it from introspection, and it seems that it flows with yet different rates for individuals from different species" (Jura 2020: 6).

However, there are reasons to doubt that temporal resolution tracks differences in the subjective experience of time. Increases in temporal resolution (as measured by increases in CFF) may enable faster reflexes without any accompanying increase in the rate of subjective experience. Much of the sensory information that animals (including humans) absorb is processed unconsciously. Differences in the speed of unconscious reflexes don't reveal anything about subjective experience. We know that spinal cord reflexes operate more quickly than conscious experience. Many impressively quick reflexes in the animal kingdom are also probably reflex-driven. The flight stabilization mechanisms that allow hummingbirds to flit from flower to flower in the blink of an eye probably operate below conscious awareness. In flies, tracking and pursuit initiation mechanisms are triggered by fairly simple rules and appear to be hardwired. Moreover, there is some limited experimental evidence that CFF values do not increase during frightening events, even when duration estimates increase (Stetson, Fiesta, & Eagleman 2007).

Case Study: Birdsong

A final independent line of evidence for differences in the subjective experience of time is birdsong. Although the argument deserves more scrutiny than it is afforded here, the intricate system of call and response that has evolved among some songbirds suggests that those birds are characteristically experiencing time at a different rate than that of humans. By many measures, songbirds display extraordinary temporal processing (Lohr, Dooling, & Bartone 2006: 247).[36] For instance, "Zebra Finch contact calls have very short fundamental periods of about 1.5–2.0 ms, shorter than most estimates of temporal resolution in the human auditory system" (Dooling & Lohr 2006: 15).[37] Unlike flight control reflexes, it seems like birdsong is probably consciously produced and consciously experienced. If that's right, then it's plausible zebra finches require a faster rate of subjective experience than humans (and other terrestrial mammals) in order to register and respond to the calls of conspecifics.[38] Ornithologists appear to have advanced just such a hypothesis: "the results we have reviewed suggests that the **avian auditory system may effectively be 'stretching' time** when perceiving complex sounds such as species-typical vocalizations. Spectrographic analysis would miss such detail—perhaps in a sense confirming the classic refrain of avian ethologists that much of the complexity in **bird song cannot be appreciated by human hearing unless the tape is slowed down**" (Dooling & Lohr 2006: 20, emphasis added).[39]

This claim is suggestive, but it's unclear exactly what it proves. As an analogy, consider a native speaker of some language communicating with a person who is proficient but not adept in the language. If the native speaker speaks slowly, the non-native speaker can understand the speech. However, if the native speaker speaks quickly, the non-native speaker quickly loses track of individual words and no longer understands the speech. A fellow native speaker, by contrast, is easily able to follow the rapid speech. Does that mean that the fellow native speaker perceives time as slowed down compared to the non-native speaker? No.[40] The native speaker is just better able to process the rapid spoken information than the non-native speaker. Similarly, songbirds

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36 "Studies of the peripheral and central auditory systems of birds have long suggested that birds should have extremely fine temporal processing abilities" (Lohr, Dooling, & Bartone 2006: 247).

37 That's about an order of magnitude faster than humans (Leshowitz 1971).

38 "In these experiments we have shown that birds can discriminate subtle temporal changes within the context of differences typically found in their natural vocal communication signals. Our results support more recent studies of peripheral auditory sensitivity in birds that have begun to demonstrate their enhanced temporal acuity, beyond the abilities reported for humans and many other mammals" (Lohr, Dooling, & Bartone 2006: 249).

39 One intriguing aspect of the songbird example is that it appears as if differences in the subjective experience of time emerged as a product of sexual selection (mating calls are a key determinant of reproductive success) rather than the usual survival-of-the-fittest selection. It would be interesting to compare the reaction time and decision-making speed of a songbird against a comparably sized non-songbird that inhabits the same ecological niche. Thanks to Gavin Taylor for noticing this point.

40 After all, it's not as if the native speaker perceives the other native speaker's lips moving more slowly than the non-native speaker does.

may just be better able to process rapid birdsong than humans.[41] Of course, the analogy is not perfect. As the non-native

speaker continues to study the foreign language, she will get better at understanding rapid speech. The difference between human understanding of birdsong and avian understanding of birdsong appears more permanent, perhaps fixed by physiological differences between birds and humans. As a different analogy, no matter how hard a human practices or studies, she will never be able to naturally see infrared light like a vampire bat does. It is as yet unclear which analogy (if either) is more apt.

Potential Proxies for the Subjective Experience of Time
Below I discuss thirteen potential proxies for the subjective experience of time. (For ease of exposition, I will hereafter drop the 'potential' in 'potential proxies.') I have divided the proxies into three categories. **Neurological measures** track the speed with which an animal's central nervous system sends and receives signals. **Behavioral measures** track the speed with which an animal responds to external stimuli. **Temporal resolution measures** track the rate at which an animal's perceptual system samples information about its environment. This tripartite classification is a useful organizing tool, but it is neither exhaustive nor conceptually deep.[42] Nor is it the case that each metric in each category is equally informative. My aim in this piece is not to offer a comprehensive catalogue of potential proxies but rather a representative sampling of potential measures.

Each of the proxies I discuss is empirically measurable with current scientific tools. However, there are large differences in the extent to which the proxies have been investigated across species. Critical flicker-fusion frequency (CFF), a measure of temporal resolution, is the most diversely studied proxy. It has been studied in at least 70 species across 30+ orders and 3 phyla. Many other proxies have only been well-studied in mammals. With the right funding, such studies could probably be expanded to non-mammalian vertebrates and to some invertebrates.

Finally, it's important to remember that all metrics that measure complicated phenomena are subject to some amount of random noise and most measures are biased under some conditions. The goal is not to find a *perfect* proxy for the subjective experience of time. In all likelihood, none exist. I would count it a success if we found a measure that roughly tracks the subjective experience of time for some animals under some conditions. As such, no single measure should be weighted too heavily. However, when multiple independent proxies all point in the same direction, we can be reasonably confident that they probably indicate some fundamental difference in the subjective experience of time.

Neurological Measures

In computers, *clock speed* is the rate at which a microprocessor executes operations. Clock speed is an important determinant of a computer's processing power.[43] All other things equal, the faster a computer's clock speed, the more operations it can execute in a given unit of time. If biological brains are analogous in important respects with computers,[44] then the speed at which an animal's brain can send and receive signals may determine, in whole or in part, the brain's 'clock speed.' Differences in neurological clock speed may generate differences in the subjective experience of time, though there is no guarantee that this would occur.[45] (See Appendix 2 for more discussion of theoretical models of temporal representation.)

The speed at which an animal's central nervous system can send and receive signals depends on four main factors: (1) interneuronal distance, (2) transsynaptic transmission time, (3) axon diameter, and (4) axon myelination (Roth & Dicke 2017: 142). Although I discuss these four factors separately, it might be conceptually more appropriate to think that they collectively constitute a single potential proxy.

Interneuronal distance is a measure of the space between neurons, sometimes reported equivalently as *neuron packing density*. All else equal, neurons that are closer together can communicate faster than neurons that are farther apart. Two brains might contain the same absolute number of neurons, but if the neurons are packed into a smaller volume in one brain, then that brain will have a significant advantage because "a short interneuronal dis-

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41 An alternate deflationary explanation is that the birds are storing the audio signals at a fine temporal resolution in simple 'cache registers,' which are then processed more slowly. This idea could be tested experimentally by investigating the minimum delay between a bird hearing birdsong and the bird responding to it. Thanks to Remmelt Ellen for the suggestion.

42 For instance, behavioral procedures are sometimes used to assess temporal resolution, blurring the distinction between the two categories. And differences in neurological features might be ultimately responsible for differences in behavioral features and temporal resolution, making neurological features conceptually more fundamental.

43 There are, however, many other determinants of processing power. In the early days of computers, clock speed was a decent proxy for overall performance. For modern computers, however, clock speed is an increasingly poor metric by which to judge processing power.

44 There are, however, many reasons to be skeptical of the brain-computer metaphor.

45 A faster clock speed might make unconscious processing more efficient without affecting the speed at which information is represented consciously.

tance, the corollary of the extremely high packing densities of their neurons, likely results in a high speed of information processing" ([Olkowicz et al 2016](#): 7259).[46] Due to both neuro-architectural differences and differences in the size of neurons, neuron densities vary across taxa. For instance, grey parrots (*Psittacus erithacus*) have roughly the same number of neurons as owl monkeys (*Aotus trivirgatus*) despite brains only half as large.[47] (See Figure 2.) Among vertebrates, parrots and songbirds tend to have the smallest interneuronal distances, and elephants, dolphins, and whales tend to have the largest interneuronal distances.
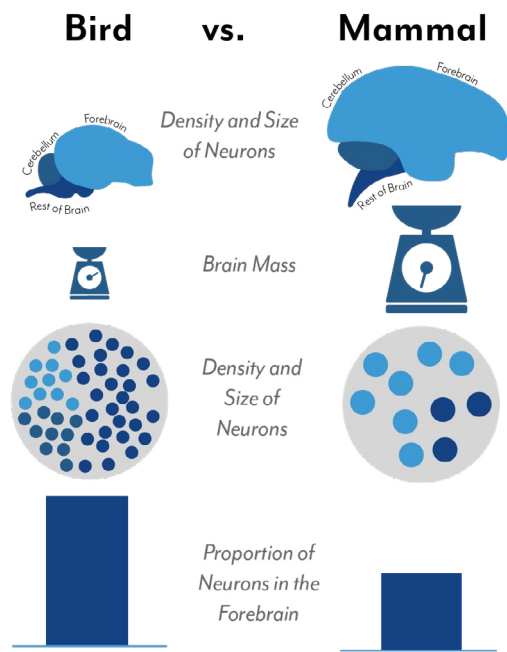

Figure 2: Birds tend to have smaller interneuronal distances because their neurons are smaller and more densely packed (source: Pavel Němec, via "[Are you smarter than a macaw?](#)")

Transsynaptic transmission time refers to the speed with which a synapse can pass a chemical or electrical signal to another neuron or target cell. The faster the signal can traverse the physical gap between cells, the faster information can be transmitted to different parts of the brain or body. Importantly, transsynaptic transmission time is not uniform across the central nervous system. Electrical synapses have a much quicker transsynaptic transmission time than chemical synapses, and in many animals,

the brain regions that govern startle and escape reflexes (which need to be very rapid) are characterized by faster transsynaptic transmission. In general, transsynaptic transmission times don't differ much among terrestrial mammals ([More & Donelan 2018](#): 3), but it is unclear how terrestrial mammals compare to other groups of animals.

Axon diameter and **axon myelination** jointly determine *axonal conduction velocity*, the speed at which signals can be sent along nerve fibers. Axonal conduction velocity increases with axon diameter: thicker nerves transmit signals faster.[48] In most animals, axon diameter isn't uniform. Some axons are much thicker than others. In humans, the auditory and vestibular axons are the thickest, giving these axons improved temporal precision and higher information rates ([Perge et al 2012](#): 636).

Myelin is an insulation sheath found around some nerve fibers. Myelinated axons transmit signals faster than unmyelinated axons. The size of the myelin sheath is not uniform across species. Among mammals, the myelin sheath is thickest in primates and thinnest in elephants and cetaceans ([Roth & Dicke 2017](#): 142). Myelination is only found in vertebrates, though not all axons in a vertebrates' nervous system are myelinated. Invertebrates, especially cephalopods, have mostly adopted the evolutionary strategy of increasing axon diameter to increase axonal conduction velocity ([Salzer & Zalc 2016](#): R972).

Because animals contain a wide variety of axons of different sizes and degrees of myelination, there is no single velocity at which signals are transmitted through the nervous system. In humans, axonal conduction velocity ranges from ~0.5 m/s to ~120 m/s ([Purves 2000](#)).[49] For this reason, it would be hard to compare axonal conduction velocity across species. In sufficiently neurologically similar animals, one could compare the axonal conduction velocities of homologous nerve fibers. It's not clear how far this approach would take you nor how valuable the comparison would be.

Another metric that might be investigated is **neuronal firing rates**. However, this is probably not a good proxy for the subjective experience of time.[50] Different parts of the brain fire at dif-

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46 This is one reason (among many) that comparing animals in terms of neuron count can be misleading.

47 See [Olkowicz et al 2016](#) for the grey parrot estimate and [Herculano-Houzel et al. 2007](#) for the owl monkey estimate. See [McCaslin 2019](#) for general discussion.

48 Doubling axonal diameter increases signal velocity by about 40% ([Fox 2011](#): 40).

49 Interestingly, the axons of newborn humans are typically only about half as fast as adult axons. Children normally reach the adult value by 3 or 4 years old ([Shelat 2019](#)).

50 Similarly, differences in brain metabolism across species probably tell us relatively little about differences in the subjective experience of time. More complex brains probably require more metabolic energy. But there are many ways in which a brain can be more or less complex that appear unlikely to influence the subjective experience of time.

ferent rates and with different regularity. Among mammals, homologous brain regions appear to exhibit similar firing regimes despite differences in brain size ([Mochizuki et al. 2016](#)).

Behavioral Measures

If animals do differ significantly in their subjective experience of time, the best causal explanation of these differences will probably appeal to differences in the speed at which certain neurological signals propagate and are processed. However, the foregoing doesn't entail that neurological measures are our best *proxy* for differences in the subjective experience of time. The neurological mechanisms that give rise to differences in the subjective experience of time might be too hard to measure and compare across species, especially when the neural architecture of the compared animals differs considerably.

Our best current evidence for differences in the subjective experience of time may be behavioral. Many animal behaviors are more easily explained if we posit differences in the subjective experience of time. If our best explanations appeal to differences in the subjective experience of time, then, in the absence of defeaters, we are licensed to prefer the supposition that such differences exist.

Some of these behaviors have already been discussed above.

Songbirds act on information in birdsong that humans can only discern if the birdsong is slowed down. This suggests that the songbirds experience the world at a faster rate than humans. Some small animals appear to respond to stimuli amazingly fast. [This video](#) shows a fly leaving a flower as a bee approaches, then immediately returning to the flower.[51] The elapsed time is less than a second. The decision to return to the flower is not obviously purely reflexive. Such a quick decision is perhaps more explicable if we posit that the fly's rate of subjective experience is faster than our own.[52] Rats can discriminate and begin responding to a novel odor in as little as 140 ms ([Wesson et al. 2008](#)). Mice, moths, and honey bees also exhibit extremely fast odor detection, with both responding to odors in as little as 200 ms ([Abraham et al. 2004](#); [Cardé & Willis 2008](#); [Wright, Carlton, & Smith 2009](#)).[53]

Unfortunately, quantifying such behaviors in a way that enables them to be compared across species is not easy. **Reaction times** have been investigated in a wide variety of animals. (See Figure 3.) These studies generally confirm that smaller animals react faster than larger animals. However, the sort of reactions that are studied in the literature are almost always the sort of reactions that we would expect to be initiated unconsciously. While perhaps suggestive, these studies provide little direct evidence for differences in the subjective experience of time.
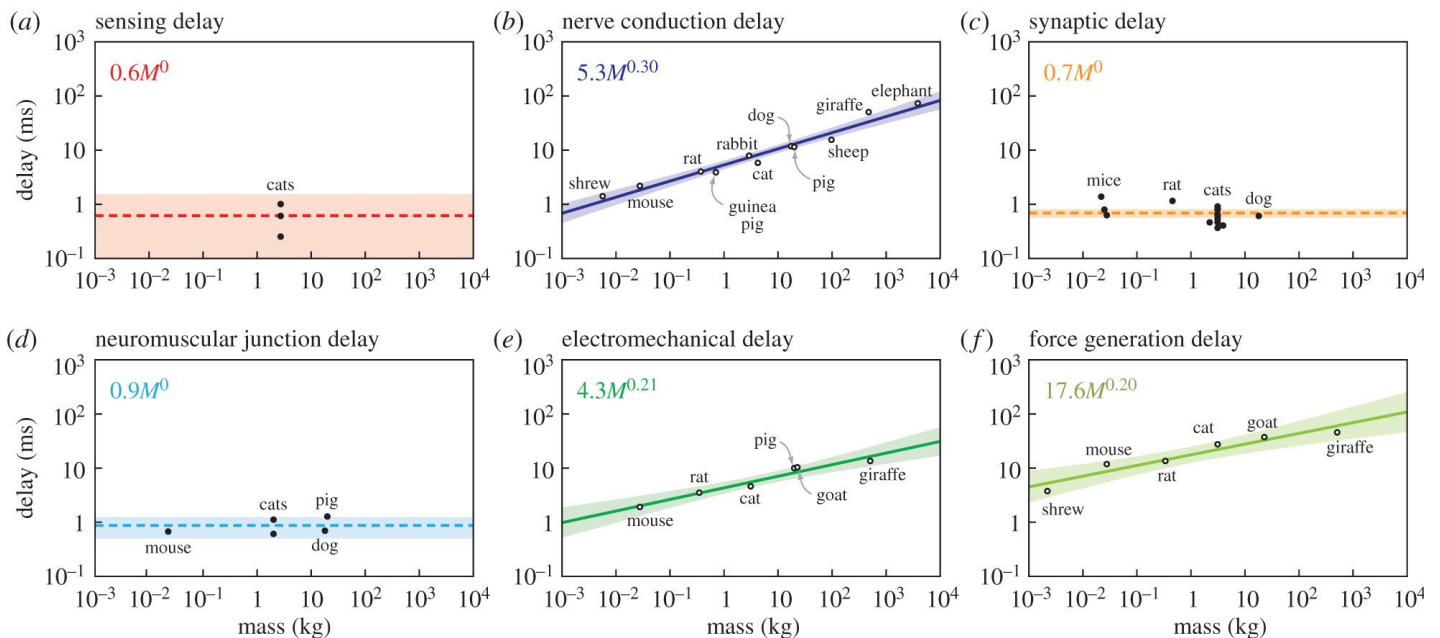

Figure 3: Comprehensive review of the contributors to reaction time in terrestrial mammals (source: [More & Donelan 2018](#): 3)

51 Video credit: Emily Baird

52 It's possible that as the bee approaches the flower, the fly formulates a plan to leave the flower and then immediately return. In that scenario, the decision to return is not made mid-flight, and so the speed of the decision need not be as quick.

53 Compare to crabs who "begin rapid locomotion only 500–600 ms after their antennules intercept an odor pulse" ([Reidenbach & Koehl 2011](#): 3139).

Ideally what we would like are studies that compare differences in *conscious* decision-making speed. One potential way to identify conscious decisions is to train nonhuman animals on an **attentional blink** paradigm. Attentional blink is the tiny gap in conscious attention that results from shifting one's focus between stimuli. Attentional blink can be measured experimentally by measuring the minimum duration at which two targets can be correctly identified. (See Figure 4.) In humans, if the targets are presented in rapid succession, roughly 100 ms apart, they are both consciously processed and are likely to be correctly identified. If the targets are separated by a duration of more than ~700 ms, they are also likely to be correctly identified. However, for targets presented roughly 300 ms apart, the second target is much harder to identify.[54] This represents the length of a typical human's attentional blink.[55] Recent research suggests that "individuals with better AB [attentional blink] task performance use a shorter time window to integrate information, and therefore have higher preservation of temporal information" ([Willems et al. 2016](#): 1). Measuring the attentional blink of nonhuman animals may help us understand how those animals consciously experience time.
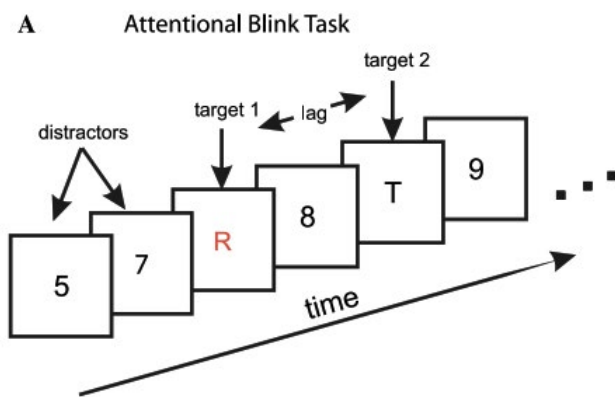

Figure 4: By altering the lag between target 1 and target 2, researchers can measure a subject's attentional blink (source: [Danckert & Allman 2005](#): 239)

Of course, the line between conscious decisions and unconscious decisions is not always clear. Hard-wired [fixed action patterns](#) can be relatively complex. But even setting aside the difficulty of distinguishing conscious decision-making from unconscious reflex or instinct, numerous hurdles remain. In general, the speed of a decision can be increased by sacrificing accuracy, and the accuracy of a decision can be improved by sacrificing speed.

Different types of decisions will call for different ways to balance speed and accuracy ([Chittka, Skorupski, & Raine 2009](#)). Thus, to compare decision-making speed across species, one would have to compare similar decision types. As the phylogenetic, ecological, and morphological differences between the compared species grows, our ability to identify relevantly similar decision types will increasingly be impaired.[56]

Temporal Resolution Measures

Even when they are awake and alert, animals, including humans, do not monitor their surroundings continuously. Instead, our perceptual systems check for new information at (mostly) fixed intervals. These intervals are so short that we generally don't perceive the gap between them, thus giving rise to the illusion of continuous perception. However, it's possible to experimentally measure the duration of these gaps. The characteristic length of the gaps varies by species.

Temporal resolution is the rate at which a perceptual system samples information about its environment. Temporal resolution is analogous to the refresh rate of a monitor. The higher a perceptual system's refresh rate, the faster it absorbs new information, resulting in a more fine-grained temporal perception of the world. Greater temporal resolution means higher temporal precision, generally enabling an animal to better track fast-moving objects in its vicinity or respond to rapidly unfolding events more quickly. (See Figure 5.)
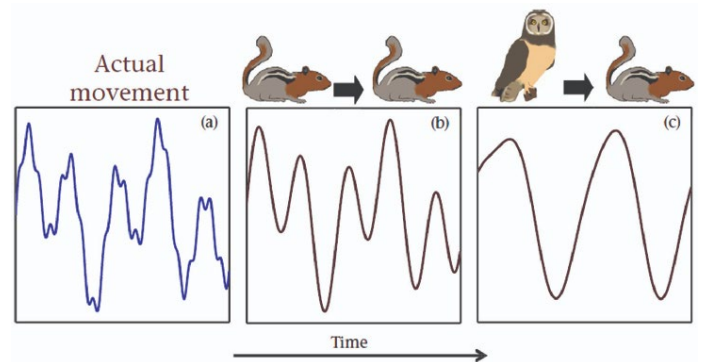
Figure 5: Difference between the actual movement of a ground squirrel [CFF = 120 Hz] (box a), the movement as perceived by a conspecific (box b), and the movement as perceived by a short-eared owl [CFF = 70 Hz] (box c) (source: [Healy et al. 2013](#): 686)

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54   "Only a tiny part of all available visual input can be perceived consciously. The process of selection happens through allocation of attention to relevant information that is present in our surroundings. Although this system of selective attention works relatively well in most situations, if two to-be-identified targets (T1 and T2) are presented in rapid temporal succession (200–500 ms), identification of T2 nevertheless frequently fails. This cognitive limitation is called the attentional blink (AB;[1]), a phenomenon that has allowed researchers to study the mechanism of temporal selective attention on the border of success and failure" ([Willems et al. 2016](#): 2).

55   See [this Scholarpedia article](#) for more detail on attentional blink.

56   Another problem is that decision-making speed varies by individual within a species. This is true even of insects like honey bees ([Muller & Chittka 2008](#)).

Under some conditions, differences in temporal resolution might be correlated with differences in the subjective experience of time. Increasing temporal resolution has energetic costs. In general, natural selection should only favor animals with better temporal resolution if (1) there are fitness-relevant fast-moving objects or quickly-unfolding events in its environment[57] and (2) the animal can take fitness-improving actions as a result of the greater temporal resolution. When the fitness-improving actions are likely to require conscious decision-making, we can expect that increases in temporal resolution will generally be accompanied by increases in the rate of subjective experience.

In principle, temporal resolution can be measured for any sensory modality. In practice, temporal resolution is widely studied for visual systems, slightly less extensively studied for auditory systems, and only very rarely studied in other senses.

Critical flicker-fusion frequency (CFF) is a well-studied measure of visual temporal resolution. I have compiled a spreadsheet comparing CFF values across 70 species and 33 orders of animals. (See Figure 6.) Green-shaded cells represent animals with higher CFF values than humans; red-shaded cells represent animals with CFF values lower than humans. (Note that the order averages in the second tab can't be interpreted literally because we don't have a representative sampling of the species from the orders.) The spreadsheet combines the values from several review articles as well as individual results from a handful of studies on species of particular interest. The spreadsheet is not intended to be comprehensive. My review of the literature was somewhat cursory, and hence I do not claim that this is an exhaustive list of the animals that have been studied. Nonetheless, I think the spreadsheet does offer a somewhat representative survey of the breadth of animals studied and the range of CFF values recorded.

(Next Page) Figure 6: CFF spreadsheet

The spreadsheet offers some somewhat surprising findings. Animals as putatively dissimilar as hermit crabs (53 Hz), humans (60 Hz), migratory locusts (65 Hz), and goldfish (67 Hz) have roughly similar CFF thresholds. On the other hand, animals as putatively similar as trout (27 Hz) and salmon (72 Hz), geckos (20 Hz) and iguanas (80 Hz), and guinea pigs (50 Hz) and ground squirrels (120 Hz), have drastically different CFF thresholds. Reptiles, insects, fish, and mammals all exhibit tremendous diversity in CFF values.

I discuss the case for and against CFF tracking the subjective experience of time in much more detail in the next post in this series. As of June 2020, I estimate there is approximately a 40% chance that CFF roughly tracks the subjective experience of time for animals that characteristically inhabit bright environments, rely predominantly on vision to learn about the world, and exhibit high behavioral plasticity.

For animals that rely on senses other than vision, CFF is not a good proxy for the subjective experience of time. Fortunately, we can measure the temporal resolution of other types of perceptual systems. When applied to audition, "[t]emporal resolution refers to the precision with which the auditory system can extract time-varying information from acoustic stimuli" (Gall, Henry, & Lucas 2012: 61). To measure the temporal resolution of auditory perception, scientists have used **auditory-evoked potentials** and **auditory flutter-fusion thresholds**. The temporal resolution of auditory systems has been extensively studied in birds and mammals and occasionally in fish,[58] but much less so in other taxa. To facilitate useful comparisons across species, it would be helpful to have more and more diverse data on auditory temporal resolution, especially from animals that humans exploit in large numbers.

Odontocete marine mammals (i.e., dolphins, porpoises, and toothed whales) appear to have the highest auditory temporal resolution of all animals thus far studied. These animals use echolocation to hunt prey. The ability to quickly process fast-traveling underwater sound allows them to track prey better and thus confers a fitness advantage. The white-beaked dolphin (*Lagenorhynchus albirostris*) has an auditory temporal resolution approximately ten times greater than humans (Mooney et al. 2009: 375).[59] Among terrestrial vertebrates, songbirds (suborder *Passeri*, e.g. finches and sparrows) appear to have the best auditory temporal resolution. These animals use complex birdsong to communicate identity, location, and sexual intentions. Studied species in this taxon generally have auditory temporal resolution 3-5 times finer than humans (Dooling & Lohr 2006: 15), which ranks them better than most terrestrial mammals but worse than odontocete marine mammals (Henry et al. 2011: 358).

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57 The most obvious examples are prey species with fast-moving predators and predator species with fast-moving prey.

58 See, e.g., Wysocki & Ladich 2002.

59 "The estimated maximal temporal resolution of white-beaked dolphins and other odontocetes was approximately twice that of pinnipeds and manatees, and more than ten-times faster than humans and gerbils. The exceptionally high temporal resolution abilities of odontocetes are likely due primarily to echolocation capabilities that require rapid processing of acoustic cues" (Mooney et al. 2009: 375).

Figure 6: CFF spreadsheet

Phylum	Class	Order	Species	Common Name	CFF (Hz)
Chordata	Amphibia	Anura	Bufo marinus	Cane Toad	6.7
Arthropoda	Arachnida	Araneae	Lycosa baltimoriana	Wolf Spider	10
Arthropoda	Malacostraca	Isopoda	Glyptonotus antarcticus	Isopod	11
Chordata	Actinopterygii	Anguilliformes	Anguilla anguilla	European Eel	14
Arthropoda	Malacostraca	Decapoda	Plesionika rossignoli	Pandalid Shrimp	14
Chordata	Reptilia	Testudines	Dermochelys coriacea	Leatherback Sea Turtle	15
Arthropoda	Malacostraca	Decapoda	Pasiphaea multidentata	Glass Shrimp	17
Arthropoda	Malacostraca	Decapoda	Sergestes arcticus	Sergestid Shrimp	17
Chordata	Chondrichthyes	Carcharhiniformes	Carcharhinus acronotus	Blacknose Shark	18
Arthropoda	Malacostraca	Decapoda	Acanthephyra purpurea	Oplophorid Shrimp	18
Chordata	Reptilia	Squamata	Gekko gecko	Tokay Gecko	20
Arthropoda	Malacostraca	Decapoda	Funchalia villosa	Penaeid Shrimp	21
Chordata	Amphibia	Anura	Rana clamitans	Green Frog	21
Arthropoda	Malacostraca	Decapoda	Systellaspis debilis	Oplophorid Shrimp	21
Chordata	Actinopterygii	Istiophoriformes	Xiphias gladius	Swordfish	22
Arthropoda	Malacostraca	Decapoda	Sergia grandis	Sergestid Shrimp	22
Arthropoda	Malacostraca	Euphausiacea	Meganyctiphanes norvegica	Euphausiid Krill	23
Arthropoda	Malacostraca	Euphausiacea	Euphausia gibboides	Euphausiid Krill	24
Arthropoda	Malacostraca	Decapoda	Sergia filictum	Sergestid Shrimp	24
Chordata	Actinopterygii	Salmoniformes	Oncorhynchus mykiss	Rainbow Trout	27
Chordata	Chondrichthyes	Carcharhiniformes	Sphyrna lewini	Scalloped Hammerhead	27.3
Chordata	Chondrichthyes	Rajiformes	Raja erinacea	Little Skate	30
Chordata	Amphibia	Urodela	Ambystoma tigrinum	Tiger Salamander	30
Arthropoda	Malacostraca	Decapoda	Janicella spinicauda	Oplophorid Shrimp	31
Arthropoda	Malacostraca	Decapoda	Oplophorus gracilirostris	Oplophorid Shrimp	32
Chordata	Mammalia	Carnivora	Pagophilus groenlandicus	Harp Seal	32.7
Chordata	Chondrichthyes	Carcharhiniformes	Negaprion brevirostris	Lemon Shark	37
Chordata	Actinopterygii	Beloniformes	Oryzias latipes	Japanese Rice Fish	37.2
Chordata	Mammalia	Rodentia	Rattus norvegicus	Brown Rat	39
Chordata	Reptilia	Testudines	Caretta caretta	Loggerhead Sea Turtle	40
Chordata	Reptilia	Testudines	Chelonia mydas	Green Sea Turtle	40
Arthropoda	Malacostraca	Euphausiacea	Stylocheiron maximum	Euphausiid Krill	40
Arthropoda	Arachnida	Araneae	Maevia inclemens	Jumping Spider	40
Mollusca	Cephalopoda	Sepiida	Sepia officinalis	Common cuttlefish	42
Arthropoda	Insecta	Blattodea	Periplaneta americana	American Cockroach	42.5
Arthropoda	Malacostraca	Euphausiacea	Nematobrachion flexipes	Euphausiid Krill	44
Chordata	Aves	Strigiformes	Bubo virginianus	Great-Horned Owl	45
Chordata	Reptilia	Rhynchocephalia	Sphenodon punctatus	Tuatara	45.6
Chordata	Mammalia	Rodentia	Cavia porcellus	Guinea Pig	50
Arthropoda	Malacostraca	Decapoda	Cambarus spp	American Crayfish	53
Arthropoda	Malacostraca	Decapoda	Pagurus spp	Hermit Crab	53
Chordata	Mammalia	Carnivora	Felis catus	Cat	55
Arthropoda	Malacostraca	Euphausiacea	Nematobrachion sexspinosus	Euphausiid Krill	56
Chordata	Mammalia	Primates	Homo sapiens	Human	60
Chordata	Mammalia	Rodentia	Tamiasciurus hudsonicus	American Red Squirrel	60
Arthropoda	Insecta	Orthoptera	Locusta migratoria	Migratory Locust	65
Chordata	Actinopterygii	Cypriniformes	Carassius auratus	Goldfish	67
Chordata	Reptilia	Squamata	Anolis cristatellus	Anolis Lizard	70
Chordata	Aves	Strigiformes	Asio flammeus	Short-Eared Owl	70
Arthropoda	Insecta	Lepidoptera	Antheraea pernyi	Chinese Tussah Moth	70
Mollusca	Cephalopoda	Octopoda	Octopus vulgaris	Common octopus	72
Arthropoda	Actinopterygii	Salmoniformes	Salmo salar	Atlantic Salmon	72
Chordata	Aves	Psittaciformes	Melopsittacus undulatus	Budgerigar	74
Arthropoda	Insecta	Lepidoptera	Saturnia pavonia	Emperor Moth	75
Chordata	Mammalia	Carnivora	Canis lupus familiaris	Dog	80
Chordata	Actinopterygii	Scombriformes	Thunnus albacares	Yellowfin Tuna	80
Chordata	Reptilia	Squamata	Iguana iguana	Green Iguana	80
Arthropoda	Insecta	Diptera	Drosophila hydei	Fruit Fly	80
Chordata	Aves	Galliformes	Gallus gallus domesticus	Chicken	87
Chordata	Mammalia	Scandentia	Tupaia glis	Common Treeshrew	90
Chordata	Mammalia	Primates	Macaca mulatta	Rhesus Macaque	95
Chordata	Aves	Columbiformes	Columba livia	Rock Dove	100
Chordata	Aves	Passeriformes	Sturnus vulgaris	Common Starling	100
Chordata	Mammalia	Rodentia	Tamias amoenus	Yellow-Pine Chipmunk	100
Chordata	Mammalia	Rodentia	Spermophilus lateralis	Golden-Mantled Ground Squirrel	120
Chordata	Aves	Passeriformes	Cyanistes caeruleus	Blue Tit	131
Chordata	Aves	Passeriformes	Ficedula albicollis	Collared Flycatcher	141
Arthropoda	Insecta	Diptera	Glossina morsitans	Tsetse Fly	145
Chordata	Aves	Passeriformes	Ficedula hypoleuca	Pied Flycatcher	146
Arthropoda	Insecta	Hymenoptera	Apis mellifera	Honey Bee	200

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Temporal resolution can be studied in yet other sensory modalities. The **temporal resolution of olfaction** has been studied in a handful of species, primarily arthropods.[60] In one study (Sehdev et al. 2019), researchers investigated the olfactory temporal resolution of fruit flies. To do so, they identified two behaviorally relevant odors, one attractive and one aversive. The flies were paired with the two odors in a wind tunnel, and the researchers varied the timing of the release of the odors. When the two odors arrived simultaneously, the flies did not move toward the combined odor. However, if the two odors arrived *asynchronously*, the flies *did* move toward the source of the odor. (The basic is that if the two odors arrive simultaneously, the flies can't pair the source of the odor with a behaviorally relevant object. However, if the two odors arrive at different times, the flies can distinguish the two odors and thus infer that there is an attractive object nearby.[61]) The researchers demonstrated that the flies could distinguish asynchronous gaps in the arrival of the odors as short as 33 ms.[62]

The olfactory temporal resolution of bees is even more impressive than flies. Szyszka et al. 2009 "found that for honeybees a 6-ms temporal difference in stimulus coherence is sufficient for odor-object segregation, showing that the temporal resolution of the olfactory system is much faster than previously thought" (1). They conclude "that honeybees can detect temporal incoherence between odorant stimuli in the millisecond range and use this information to extract odorants' identity. This seems a remarkable performance considering that the sense of smell is regarded to be a relatively slow sense as compared to the auditory or visual senses" (Szyszka et al. 2009: 3).

In addition to insects, the olfactory temporal resolution of crustaceans has also occasionally been investigated. Harzsch & Krieger 2018 report that the "temporal resolution of odor sampling" in crustaceans is "relatively slow" (31). Reidenbach & Koehl 2011 report that the olfactory temporal resolution of the American lobster (*Homarus americanus*) is 3-5 times slower than the olfactory

temporal resolution of *C. cautella* and *P. gossypiella* moths (3140). It thus appears that crustaceans have relatively poor visual and olfactory temporal resolution, while flying insects have comparatively much better visual and olfactory temporal resolution. More studies in this area could help us determine how well comparative temporal resolution correlates across sensory modalities.

Temporal Integration Windows and Cortical Oscillations

A **temporal integration window** is the minimum duration that appears to last more than a single instant. Stimuli that arrive during the same temporal integration window appear to be simultaneous. Temporal integration windows are the inverse of temporal resolution measures: the greater an animal's temporal resolution, the shorter its temporal integration window will be. Animals with shorter temporal integration windows may have faster rates of subjective experience.

Like critical flicker-fusion frequency, temporal integration windows can vary considerably even across similar animals. In humans, the minimum temporal integration window is around 40 ms, though some paradigms elicit temporal integration windows as long as ~200 ms (Melcher et al. 2014 and Wutz et al. 2016).[63] Rhesus monkeys have a minimum temporal integration window of around 25 ms (Osborne & Lisberger 2009: 2023).[64] (Compare human CFF at 60 Hz to rhesus monkey CFF at 95 Hz.)

Temporal integration windows may be governed by **cortical oscillations**.[65] (See Figure 7.) Some researchers hypothesize that "conscious perception occurs in discrete temporal windows, clocked by the frequency of alpha oscillations [citations omitted]. Under this hypothesis, variation in the frequency of occipital alpha oscillations should predict variation in the temporal resolution of visual perception. Specifically, when two stimuli fall within

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60   In what follows, I discuss the olfactory temporal resolution of honey bees and fruit flies. However, it's worth noting that insects use two types of olfactory coding, a combinatorial scheme and a labelled scheme. Odors that have labelled lines can be responded to much faster than those that require discrimination with a combinatorial code (Haverkamp, Hansson, & Knaden 2018). Thanks to Gavin Taylor for bringing this point to my attention.

61   It is unclear whether the odors are processed consciously or unconsciously and whether the fly's movement toward the odor source is the product of a simple fixed action pattern or a more centralized decision.

62   "We found that flies can detect a short difference in the arrival of two odorants (onset asynchrony of 33 ms)" (Sehdev et al. 2019: 115).

63   Interestingly, the length of one's temporal integration window seems to depend in part on one's expectations: "The temporal window in which these visual events are integrated was furthermore found to be adaptable. By varying stimulus presentation rate in a classic alphanumeric AB [attentional blink] task, it was shown that the expectation of a slow presentation rate induced more temporal integration (measured indirectly with order reversal frequency), which was thought to reflect a longer integration window. In contrast, the expectation of a fast presentation rate induced less temporal integration, which was thought to reflect a shorter integration window. The observed changes in behavior were thus interpreted as evidence for adaptive control of integration" (Willems et al. 2016: 3).

64   See Itoh et al. 2019 for more on comparisons of temporal integration windows between monkeys and humans

65   See Arnal & Giraud 2012 and Samaha et al. 2015 for helpful overview.

the same alpha cycle, they may be perceived as a single stimulus, resulting in perception with lower temporal resolution when alpha frequency is lower" ([Samaha & Postle 2015](#): 2985). Recent experimental results "support the notion that the occipital alpha rhythm may dictate the resolution at which visual information can be consciously sampled" ([Samaha & Postle 2015](#): 2988). Measuring these kinds of oscillatory brain activity in nonhuman animals may improve our understanding of the way other animals experience time.
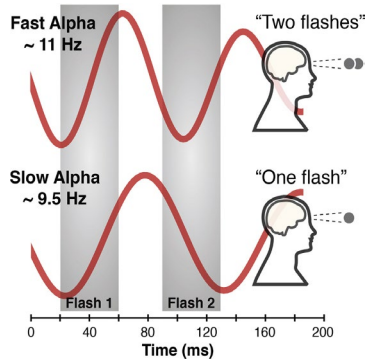

Figure 7: When two stimuli fall within the same alpha cycle, they are more likely to be perceived as one (source: [Samaha & Postle 2015](#))

How Considering the Subjective Experience of Time Could Influence Resource Allocation

To the best of my knowledge, considerations regarding characteristic differences in the subjective experience of time across species currently exert little to no influence over the way resources are allocated within the effective animal advocacy movement.[66] In large part this lack of attention is well justified. The issue is complex, and without significant care and meticulous research, it's difficult to be confident about one's views on the subject. (Even *with* significant care and meticulous research, confidence can be hard to come by!) However, I think the moment is right to start incorporating such considerations into our allocative decision-making.

Reflecting on the subjective experience of time raises four main points pertinent to the allocation of resources. The first point concerns uncertainty. Presently, the most commonly used metrics to compare the moral value of animals across species appear to be neuron count, encephalization quotient, brain mass:body mass ratio, and related measures.[67] As best as I can tell without gathering more data and conducting detailed statistical analysis, the potential proxies for the subjective experience of time correlate weakly or not at all with these measures. Thus, the proxies for the subjective experience of time suggest a much different ordinal ranking of animals than brain mass, neuron count, or encephalization quotient. (And notably, unlike the brain-related measures, humans don't come out on top of the ranking generated by time experience measures.) The general lesson is that not all morally relevant metrics point in the same direction. Brain-related measures and time-related measures both purport to express (different) morally relevant characteristics. Because there don't seem to be decisive reasons to weight brain-related measures much heavier than time-related measures, it would be prudent to give each group of metrics at least modest consideration. The fact that two groups of proxies deliver such divergent results usefully highlights our deep uncertainty with respect to the comparative moral value of different types of animals. It's not always clear what to do in the face of deep uncertainty, but in this case I think it's plausible that we ought to react by adopting a slightly more uniform distribution of resources across animals.[68]

The second point concerns diversity. To date, effective animal advocates have mostly focused on two or three taxonomic families.[69] But there are more than 50 taxonomic families of animals that humans exploit in large numbers (to say nothing of the diversity of wild animals humans don't directly exploit).[70] Unsurprisingly, these groups of animals differ from each other in many ways. Despite these differences, there is a tendency to lump many groups of animals together. People talk about *insects* (at least eight taxonomic families exploited by humans), *crustaceans* (at least ten taxonomic families exploited by humans), and *fish* (at least ten taxonomic families exploited by humans) as if they represent homogeneous categories. Measures of the subjective experience of

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66   It's possible that Brian Tomasik's 2016 blog post "[Do Smaller Animals Have Faster Subjective Experience?](#)" exerted some indirect influence. Luke Muehlhauser speculated about differences in the "clock speed of consciousness" across species in this [2018 LessWrong post](#), but it's unclear how much (if at all) those speculations have influenced his subsequent decisions.

67   In academia, see, for instance, [Budolfson and Spears 2019](#). Within effective altruism, see Dominik Peters' [ethical.diet](#), Evan Sandhoefner's [Farm Animal Suffering Comparisons](#), and this [2013 blog post](#) from Carl Shulman.

68   I've [previously estimated](#) that vertebrates currently receive more than 99% of EAA funding, and most of that money goes to terrestrial (rather than aquatic) animals. This despite the fact that fish are exploited in greater numbers than birds and mammals and despite the fact that invertebrates make up more than 99.9% of all animals on the planet.

69   I have in mind *Bovidae* (e.g., cows), *Suidae* (e.g., pigs), and *Phasianidae* (e.g., chickens), though various families of fish are beginning to receive more attention.

70   See [this spreadsheet](#) for my best accounting of the taxonomic diversity of animals exploited by humans.

time helpfully remind us that this is not the case.[71] Fish and insects in particular exhibit a huge range of temporal resolutions. (For instance, swordfish have a CFF of 22 Hz; tuna have a CFF of 80 Hz. Cockroaches have a CFF of 42 Hz; honey bees have a CFF of 200 Hz.) The lesson is that fish and insects (and to a lesser degree, crustaceans) should not be treated as if they constitute homogeneous groups with the same moral status or capacity for welfare.

The third point concerns the future. Considerations pertaining to the subjective experience of time have up until recently been largely ignored (again, with good reason) within the effective animal advocacy movement. Although there is a fairly large scientific literature on temporal perception, most (but not all) authors don't address how their research relates to the subjective experience of time. Discussions of the *moral* importance of the subjective experience of time are even rarer. All this is to say that the field is fairly neglected relative to its potential importance. Future work in this area could yield considerable early returns on investment. With the right focus, a coalition of psychologists, neuroscientists, philosophers, and animal advocates could potentially uncover a wealth of new insights. Such research might help us better prioritize among animals, especially within diverse taxa like fish, insects, and crustaceans.

The fourth and final point concerns the present. Although there is much we don't know about characteristic differences in the subjective experience of time (including whether or not such differences actually exist!), there are at least a few action-relevant items about which we can be relatively confident. Although it's unclear exactly how most animals compare to each other in terms of their subjective experience of time, the rough bounds of the distribution are visible. Judging by the potential proxies I've identified, rates of subjective experience probably don't differ by more than two orders of magnitude across the animal kingdom (assuming such differences exist at all). The characteristic human experience of time appears to be roughly in the middle of this spectrum, so nonhuman animals are unlikely to experience time more than ten times faster or ten times slower than humans.

We can even say something about specific animals. Convergent evidence suggests that songbirds and honeybees are likely to have fast rates of subjective experience (and thus merit more moral concern than comparable animals with slower rates of subjective experience). Songbirds have fantastic temporal resolution across both auditory and visual domains and their brains pack neurons together very densely, allowing for rapid communica-

tion. Honey bees also have excellent temporal resolution across multiple domains (vision and olfaction) and pack almost a million neurons in a brain less than a cubic millimeter in volume (Menzel & Giurfa 2001). Songbird and honey bee behavior appears to be more easily explained if we posit faster rates of subjective experience. Taken together, at the margin and all else equal, we should look for opportunities to improve the welfare of these animals.

Conclusion

Investigating the subjective experience of time is necessarily a speculative enterprise. There is no way to know with certainty how other individuals experience time. With fellow humans, we can usually rely on verbal reports.[72] With nonhuman animals, the best we can do is make inferences on the basis of differences in behavior, neurology, and sensory perception. Absent some radical new technology, the private mental lives of nonhuman animals will remain just that—*private*.

Although certainty is out of our reach, justified beliefs are not. By thinking carefully about this issue, engaging deeply with both the scientific literature on temporal perception and the philosophical literature on temporal experience, we can begin to piece together convergent lines of evidence suggesting which animals (if any) experience time faster or slower than humans. Incorporating insights from this topic into our moral worldview could lead us to fundamentally rethink the value we place on different sorts of animals. Of course, much uncertainty remains.

In many ways, studying differences in the subjective experience of time across species is but a proof of concept for the larger project of studying differences in capacity for welfare more generally. Some natural lessons have emerged from this trial run. First, for most morally salient characteristics, it will probably be necessary to operationalize the characteristic in more than one way. Second, for most operationalizations of morally salient characteristics, there will be holes in the empirical literature; we should reflect on the most cost-effective way to fill those holes. Third, even with near-complete empirical knowledge, our best theoretical analysis of the connection between the objective data and subjective welfare will often remain tentative; we ought to resign ourselves to and accept this inevitable uncertainty.

Finally, this: *there is still so much to discover*. I spent three months studying the subjective experience of time, and almost every day I learned something new. There has never been a comprehensive

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71 These animals also differ with respect to brain-related measures, so we shouldn't actually need to reflect on time-related measures to see this point.

72 Although even these are not decisive—there's robust debate about whether reports of differences in the subjective experience of time allegedly triggered by life-threatening events should be taken literally

investigation into the morally relevant differences among different sorts of animals. There is a wealth of knowledge waiting to be uncovered. The orchard is ripe with low-hanging fruit.

Appendix 1: Temporal Experience vs. Temporal Judgments

We ought to clearly distinguish the experience of time from the *judgments* we make about time. Under some conditions, differences in temporal experience will lead to differences in temporal judgments. Importantly though, differences in temporal judgments need not be the product of differences in temporal experience. Just as there are a number of techniques to reliably induce optical illusions, there are similarly a number of techniques to reliably induce *temporal* illusions.[73] For example, "in a repeated presentation of auditory or visual stimuli, an unexpected object of equivalent duration appears to last longer" (Pariyadath & Eagleman 2007: 1). This is known as the *oddball illusion*. (See Figure 8.) Describing the exact phenomenology of such experiences is a bit tricky, but it seems as if the oddball illusion (and its many cousins), does not affect temporal experience.[74] "The oddball and debut illusions involve distortions in duration judgments but do not affect perceived auditory pitch or high visual flicker frequencies" (Pariyadath & Eagleman 2007: 4). In other words, the oddball illusion induces a local distortion in duration estimates, but it does not have the sort of global effects we would expect if it induced a general distortion in the subjective experience of time.

In general, "time judgments show a range of task, context, and order effects" (Matthews & Meck 2016: 869). These effects can distort judgments of duration, order, and even simultaneity. "For example, perceived durations can be warped by saccades or by an oddball in a sequence. Temporal order judgments of actions and sensations can be illusorily reversed by exposure to delayed motor consequences, and simultaneity judgments can be manipulated by repeated exposure to non-simultaneous stimuli" (Stetson, Fiesta, & Eagleman 2007: 1 [citations omitted]). Estimation tasks (e.g., 'how long was that image visible?') and production tasks (e.g., 'press button when image has been on the screen for x seconds') often produce divergent results (Matthews & Meck 2014: 430-431).[75] Auditory stimuli are reliably judged longer than visual or vibrotactile stimuli of the same duration (Matthews & Meck 2016: 871). Nonhuman animals also exhibit some of these time distortions under certain conditions. (See Zentall & Singer 2008 for examples in pigeons.) Other nontemporal variables that affect temporal judgments in humans include sex differences, developmental changes, age, general intelligence, body temperature, emotional state, clinical conditions (e.g., schizophrenia, ADHD, PTSD, depression), attention, memory, prior experience with the stimulus, stimulus intensity, and the perceptual properties of the sensory input (Matthews & Meck 2016: 865).[76]

The lesson here is that not all influences that affect the judgments we make about time reflect genuine differences in the experience of time. For instance, there are good reasons animals (including humans) might be hardwired to judge that some events last longer than others. "The feeling that a stimulus lasted for a long time might be a useful subjective index of its importance, one which can combine with other perceptual, affective, and motivational cues to determine the optimum course of action" (Matthews & Meck 2016: 892). It's easy to see how evolution would favor animals that devoted more attention to novel stimuli. It has been

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73 It's perhaps helpful to consider an analogy between spatial perception and spatial estimation. When I move from looking at unadulterated straight lines to the Müller-Lyer illusion, nothing in the qualitative nature of my spatial perception has changed. The addition of the pointed arrow shafts to the straight lines reliably induces a disposition to judge that the lines are of unequal length. (If I know about the illusion I may not *actually* judge that the lines are unequal, but I still feel the pull of the disposition.) However, it's not clear that the addition of the pointed arrow shafts makes the perception of the lines *nonveridical.* After all, the Müller-Lyer illusion is exactly what two straight lines with differently pointed arrow shafts look like. In contrast, if I view two unadulterated straight lines then ingest psychedelic drugs and look at the lines again, I might judge that they are different lengths because my spatial perception has changed due to the drugs.

74 Other temporal illusions include the Kappa effect, flash-lag delay, and chronostasis.

75 Estimation tasks and production tasks ought to be inversely correlated. Suppose that one's temporal judgments are skewed by a factor of 2. Then, for an image that has been on the screen for 5 seconds, one should give an estimated duration of 10 seconds. When asked to press a button when the image has been on screen for 5 seconds, one should press the button at 2.5 seconds. Experimental results indicate that estimation tasks and production tasks often don't obey this correlation.

76 I leave open the possibility that some of these factors influence the subjective experience of time. However, I find it implausible that *all* the factors affect the subjective experience of time. So long as some factors affect temporal judgments without affecting temporal experience, we can draw a useful distinction between the two.

suggested that "estimates of duration correspond to the expenditure of neural energy used to process a stimulus" (Jura 2019: 2). So a novel stimulus (such as the deviant picture in the oddball illusion) grabs our attention, causing us to commit a greater share of neural energy to process the stimulus, thereby producing the illusion of increased duration, which makes the stimulus more salient to our conscious decision-making, thereby improving the odds that we react to the stimulus appropriately. This is a plausible story, but note that nothing in the story suggests that the subjective experience of time changes during the novel stimulus.

Appendix 2: Theoretical Models of Temporal Representation

Despite decades of investigation, there is no consensus in the literature about how the human brain represents and processes temporal information.[77] Making progress on this question could shed light on whether and how humans experience differences in the subjective experience of time, which would inform our estimate of the likelihood that other animals experience time at different subjective rates. Learning more about temporal representation and processing in human brains might also allow us to infer something directly about the temporal experience of a non-human animal by examining its brain. Thinking more generally about the various ways temporal information can be processed and represented might allow us to speculate on the way such information is processed and represented in brains significantly different from human brains.

Before discussing specific theories, it's worth noting that there is no a priori guarantee that there is a *single* way temporal information is represented and processed in the brain. Human activity depends on temporal information on many different scales, from milliseconds (for automatic reflexes) to decades (for long-term planning) and many scales in between. It's plausible that the brain represents and processes information on these different scales in different ways.[78] Some authors even suggest that the best explanation for certain experimental data is that the brain utilizes different timing mechanisms for different sensory modalities.[79]

There are two main approaches to modeling temporal representation in the brain: *centralized timing mechanisms* and *distributed, intrinsic timing mechanisms* (Muller & Nobre 2014).[80] The most popular centralized timing mechanism model is the *pacemaker-accumulator* model.[81] According to the pacemaker-accumulator model, a neurological pacemaker pulses at regular intervals, and when an external signal triggers a neurological switch, these pulses are counted by a neurological accumulator. Duration estimates are based on the number of pulses stored in the accumulator. The accuracy of duration estimation improves through childhood as one learns to better correlate the number of pulses in the accumulator with external measures of time's passage. (See Figure 9.) Though not a requirement of the model, one could imagine that pacemakers run at different speeds produce different rates of subjective experience.
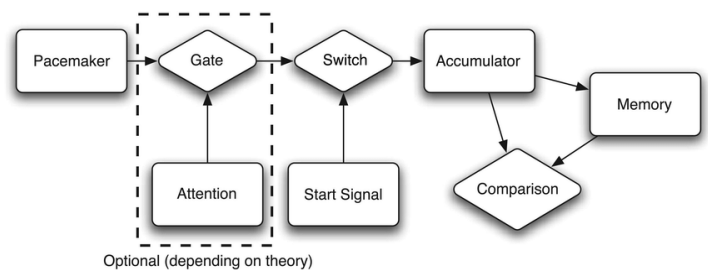

Figure 9: The Pacemaker-Accumulator Model of Temporal Representation (source: Taatgen, van Rijn, & Anderson 2007: 578)

When the field was young, psychologists assumed there was some physical mechanism dedicated to timing located in a discrete region of the brain. However, as years passed and increasingly sophisticated neurological investigations failed to reveal any distinct brain area associated exclusively (or even primarily) with temporal judgments, psychologists began to entertain the idea

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77   "The mechanisms by which the brain tracks and compares time from second to second is not understood; indeed, there is debate in the literature as to whether dedicated time-keeping mechanisms exist or whether timing-related behaviors emerge from the intrinsic properties of other circuits" (Faber 2017: 2806).

78   "Importantly, timing of intervals in the sub-second range is thought to involve different brain regions than timing of longer ones" (Jura 2019: 2).

79   "The results of our study imply that two different processing mechanisms may underlie temporal-order judgements, depending on the stimuli used. A central-timing mechanism independent of sensory modality can be assumed for the temporal-order judgement with click, colour and position stimuli. In contrast, the temporal-order of two different tones is processed by independent feature-specific mechanisms" (Fink et al. 2006: 351)

80   Ian Phillips has proposed a *relational* model of temporal representation based on level of mental activity according to which "variation in duration judgments... may be the result of variation in concurrent mental activity relative to which we measure the durations of environmental events" (Phillips 2013: 244). According to Phillips, "a purely relative account of perceived duration could make sense of duration distortions by appeal to the idea that duration is in part perceived relative to concurrent non-perceptual mental activity" (Phillips 2013: 246). Though seemingly promising, this type of account does not appear to have caught on in the literature.

81   Other popular models include the *process-decay* model and the *oscillator-coincidence detection* model.

that temporal information is processed in a distributed manner.[82] The main alternative to centralized timing mechanism models is *distributed, intrinsic timing mechanism* models.[83]

The basic idea behind most distributed, intrinsic models is that temporal representation is a product of the efficiency of neural coding; stimuli which evoke larger neural responses are perceived as longer. In other words: "temporal representations may be abstracted from time-dependent changes in local cortical networks that are activated by specific stimuli. That is, in the same way that one can infer how long ago a rock was thrown into a pond by the pattern of ripples on the surface, so the brain may extract temporal information from the pattern of neural activity triggered by the presentation of a stimulus" (Matthews & Meck 2014: 430). Again, though not a requirement of the model, one could imagine that different characteristic patterns of neural activity produce different rates of subjective experience.

Credits

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82 "the recent view is that there is no single, centralized clock in the brain, dedicated to performing any operations related to timing, regardless of the nature of a task. Instead, imaging data show that distributed brain areas are involved in time-keeping, which suggests that specialized areas have their own built-in mechanisms, that may vary among systems" (Jura 2019: 1). "At least over a short time frame, our temporal perception of events is far from veridical, and multiple timelines are capable of dynamic recalibration. This is incompatible with the notion of a unitary centralized and dedicated clock, from which all timing is performed" (Muller & Nobre 2014: 69).

83 "there is no time-sense organ or single pathway carrying temporal information from the periphery to the brain. Rather, all sensory channels support time perception, and it is unclear how far these representations are mediated by common structures and mechanisms. Moreover, timing occurs over massively varying scales, from microseconds to years, and at intermediate durations multiple mechanisms likely operate in parallel, complicating the search for simple information processing models and neural substrates" (Matthews & Meck 2014: 429).

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