Psychological Spacetime: Implications of Relativity Theory for Time Perception

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Abstract
It has been an accepted scientific fact in physics for almost 100 years that time speeds up and slows down for an observer based on factors—such as motion and gravity—that affect space. Yet this fact, drawn from the theory of relativity, has not been widely integrated into the study of the psychology of time. The present article helps to fill in this gap between physics and psychology by reviewing evidence concerning what a psychological spacetime processor—one that accounted for the theory of relativity’s empirically validated predictions of the compensatory relationship between time and space—would look like. This model of the spacetime processor suggests that humans should have a psychological mechanism for slowing time down as motion speeds up, a prediction that already has widespread research support. We also discuss several novel hypotheses directly suggested by the spacetime model and a set of related speculations that emerge when considering spacetime (some of which have already received empirical support). Finally, we compare and contrast three very different potential reasons why we might have developed a spacetime processor in the first place. We conclude that the spacetime model shows promise for organizing existing data on time perception and generating novel hypotheses for researchers to pursue. Considering how humans might process spacetime helps reduce the existing gap between our understanding of physics and our understanding of human psychology.

Keywords
time perception, spacetime, physics, relativity theory

Everyday experience thus fails to reveal how the universe really works, and that’s why a hundred years after Einstein, almost no one, not even professional physicists, feels relativity in their bones. This isn’t surprising; one is hard pressed to find the survival advantage offered by a solid grasp of relativity. Newton’s flawed conceptions of absolute space and absolute time work wonderfully well at the slow speeds and moderate gravity we encounter in daily life, so our senses are under no evolutionary pressure to develop relativistic acumen.

—Brian Greene (2004, p. 77).

The intimately woven bond between space and time—a relationship so entrenched that it is referred to by physicists as a single entity called spacetime—has been an accepted scientific fact for generations of scientists. Repeated tests have confirmed empirically that time is not the static entity that Newton imagined it to be; rather, in line with the theory of relativity, motion and gravity not only affect space but also simultaneously affect time. Time in reality slows up and slows down for each observer based on their movement through spatial dimensions in highly predictable ways (see, for example, Greene, 2004; Penrose, 2010; Shankar, 2013).

Yet, in spite of this long-accepted fact in physics, the notion of spacetime has received curiously little attention from psychologists studying time perception. We suspect that this is very likely because most academics share prominent physicist Brian Greene’s (2004) assessment—illustrated in the above quote—of the relationship between actual spacetime and our perception of spacetime. That assessment could be summarized as follows: Who needs it? After all, if the added predictive “everyday” value of spacetime perception is so small that it conveys no survival advantage at all, then why would we have ever developed a mechanism to account for it? And if we would not have ever developed such a mechanism, why bother thinking about the relationship between our psychological functioning and spacetime in the first place?

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Why Should Psychology Researchers Care About Psychological Spacetime?

The sentiment is understandable. Yet we nonetheless believe that there are at least two separate reasons to care about psychological spacetime. First, available evidence suggests that the psychology of time and the psychology of space are in reality intimately bound up; and yet this fact is rarely tied to the physical relationship between time and space. For example, positron emission tomography (PET) and functional magnetic resonance imaging (FMRI) studies suggest that time perception and motion perception systems have quite a bit of direct overlap in shared biological space in the brain (Coull, Frith, Buchel, & Nobre, 2000; Coull & Nobre, 1998; Doherty, Rao, Mesulam, & Nobre, 2005; Griffin & Nobre, 2005; Janssen & Shadlen, 2005; for a review, see Eagleman et al., 2005). Similar work reveals that localized hemispheric deficits in space perceptions show corresponding deficits in time perception, further suggesting that “representations of space and time share neural underpinnings” (Saj, Fuhrman, & Vuilleumier, 2014, p. 207; for related evidence, see Mauk & Buonomano, 2004). Although this overlap does not mean we have a spacetime processor in line with relativity theory, it is at least consistent with the notion that space and time are perhaps more intricately bound up in human psychology than a Newtonian processor might expect. Thus, it is worth more fully conceptually and empirically exploring the nature of this overlap, and the actual operation of space and time in physics is one potential guiding model to aid our understanding.

Second, we have at times in history underestimated the human capacity for sensing and assimilating information from the environment. For example, 100 years ago, few would have predicted the profound ability of the human psyche to sense, interpret, and assimilate information presented below the level of conscious awareness, or the degree that human psychology occurs beyond our explicit knowledge or consent. Yet, today, such unconscious and implicit effects are accepted scientific fact (see, for example, Bargh & Chartrand, 1999; Conway, 2004; Hsieh & Colas, 2012; Kouider, de Gardelle, Dehaene, Dupoux, & Pallier, 2010; Proulx & Heine, 2008). For example, research demonstrates that one can implicitly prime stereotypical schemas and alter subsequent behavior in ways consistent with the stereotype—such as slowing down persons’ walking speed by priming words related to “old”—without persons being consciously aware that the process is happening (see Bargh & Chartrand, 1999).

Although our species has only recently begun to articulate the concepts of spacetime, it seems nearly certain that physical spacetime has existed in its present integrative form throughout human history. As such, any evolutionary processes acting upon our species would have acted in the constant presence of such spacetime as a certain reality, and thus it is perhaps premature to dismiss out of hand the possibility that we do have some mechanisms that aid us in the integrative perception of spacetime. And, as we shall see below, some research suggests that we may indeed have spacetime-like mechanisms for perceiving the intimate, relativistic relation between space and time.

The implications of understanding the psychological overlap between space and time are vast. To the degree that humans do possess spacetime-like processors, understanding those mechanisms could contribute a great deal to our fundamental understanding of how humans process time. The largely untested set of hypotheses generated by the new proposed model could importantly alter our understanding of the psychology of time.

This is no small matter: The psychological processing of time has multiple practical implications for human emotion, life satisfaction, and mental health (e.g., Carstensen, Isaacowitz, & Charles, 1999; Conway, 2004; Droit-Volet, Fayolle, & Gil, 2011; Droit-Volet & Meck, 2007; Flaherty, 1991; Fredrickson, Mancuso, Branigan, & Tugade, 2000; Gil & Droit-Volet, 2009, 2012; Hawkins, French, Crawford, & Enzle, 1988; Rowe, Hirsh, & Anderson, 2007; Zimbardo & Boyd, 2008). If how people process time is altered by space and motion (as we discuss below), then interventions that use time as a mechanism for improving life quality could be potentially improved by including considerations of space and motion.

The Present Article

The purpose of the present article is to address this gap between physical spacetime and the psychology of time. Our primary method to accomplish this goal is to consider what a spacetime processor—one that processed spacetime in line with relativity theory—would look like if humans possessed it. As we discuss below, our model does not (necessarily) predict that physical spacetime and psychological spacetime directly overlap in one-to-one correspondence. It rather suggests larger directional principles concerning how we would process the relationship between space and time.

To illustrate our model, we discuss a set of predictions that can be made, when considering physical spacetime, about how people might perceive time and space. This includes a substantial research literature supporting one of the key predictions from our newly conceptualized psychological spacetime model, as well as additional novel hypotheses that have yet to be tested. We then discuss a set of related speculations that emerge when considering spacetime. Finally, we compare and contrast three very different potential reasons why we might have developed a spacetime processor in the first place.

The Backstory Sketch of a Spacetime Processor

The theory of relativity suggests that movements through time and space are compensatory, so that movement through space affects movement through time and vice versa. This
means that if we perceived spacetime in line with relativity, we would have mechanisms that would in some way correspond to this interaction between time and space. It further suggests that all things that “bend” space or alter motion—such as gravity—would also affect time perception. Below, we discuss what we might expect to find in a human processor if, in fact, there were mechanisms for processing spacetime in this manner. Before doing so, however, it is necessary to first discuss, write large, how human processes typically interface with the real world.

**Human Processing Involves Exaggerated Comparative Perceptions**

No human processing mechanism interfaces with physical reality by producing a one-to-one correspondence with that reality. We do not “copy” reality into our mind; it is always a reconstructive process. For example, from the moment light photons hit the eye, the visual system is reconstructing, altering, transmuting, and adapting the reality “out there” into an image “in here” (see, for example, Weiten, 2013). As a result, it would be unrealistic to expect that a human psychological mechanism would exist that might produce an exact replication of spacetime in the human mind. Rather, if we look across known human processing mechanisms, what we see instead are a series of exaggerations and perceptual heuristics that roughly correspond, most of the time, to something “out there.” So, for example, our mechanisms for distinguishing objects in our environment involve a series of processes that essentially exaggerate differences between features in our visual world: We have systems that visually enhance edges, systems that overemphasize clustering of like stimuli, and systems that finish apparently unfinished familiar objects (see, for example, Weiten, 2013).

These perceptions do not exist in a vacuum and, as a result, are often as responsive to relative changes on a particular variable as to the absolute level of that variable (see Cialdini, 2001). A common example involves judgments of temperature—A 70-degree room will feel hot if someone enters it from a 40-degree environment, but the same 70-degree room will feel cold if a person enters it from a 100-degree environment. This simple example illustrates that we often process changes in the general direction (e.g., hot to cold, cold to hot) of variables as much as we process the absolute level of those variables.

As a result of this general tendency to have exaggerated comparative perceptual mechanisms, what we might expect to find in terms of our psychological interface with spacetime is not a one-to-one measurement of spacetime, but rather a set of similarly exaggerated mechanisms for perceiving the general direction of the relationship between the variables involved in spacetime alterations. This looser perspective suggests a set of hypotheses (described in detail later in this article) about how we ought to perceive the general relationship between space and time as a corollary to their actual physical relationship.

**Human Processing Involves Perceptions of Observable Markers**

Time perception is highly malleable (see, for example, Conway, 2004; Droit-Volet et al., 2011; Droit-Volet & Meck, 2007; Flaherty, 1991). For such malleable systems, human processing most typically involves perceptions of observable markers of objective reality and not the underlying reality itself. For example, evolutionary psychology theories of mate selection emphasize that we do not have a direct line to the “fertility” of a particular mate; rather, there are markers that themselves are correlated with fertility (e.g., markers of age, beauty, health), and it is those markers that we use (e.g., Buss & Schmitt, 2011). Similarly, there are markers of whether or not someone is related to us (Park, Schaller, & Van Vugt, 2008), or whether or not someone has a disease that might harm us (Park, Schaller, & Crandall, 2007). These markers are not direct lines to kinship or disease; they are rather observable indicators that are correlated with those factors.

When we are thinking of how we might process spacetime, it is likely that we have mechanisms that note observable markers in our world that alter time perception, much in the same way we might assume that someone with a symmetrical face is more likely to be fertile. This would mean that, as in the case of fertility markers, the markers will sometimes not correspond to reality in a given instance. Much evolutionary psychology suggests that we have psychological modules that operate in this manner (e.g., Buss & Schmitt, 2011).

As a result, it is not necessarily the case that we have to be experiencing spacetime alterations ourselves to show the effect of the markers. As an example, consider that if we have a heuristic that suggests “darkness = exaggerate danger-related traits,” we do not need to feel “in danger” for the heuristic to cause the expected outcome (e.g., Schaller, Park, & Mueller, 2003). Similarly, many of the hypotheses suggested by spacetime may not require people to actually experience spacetime alterations; but rather, people may have corresponding implicit mechanisms to alter their time perceptions based on observable markers that are generally associated with spacetime changes.

**What Would a Spacetime Processor Look Like?**

Having painted a sketch in broad brushstrokes of how we might expect a psychological spacetime processor to interface with the real world, we now turn our attention to the features a spacetime processor should possess. To do so, we lay out some specific psychological factors we would expect a time perception processor to operate on if it corresponded...
in some way to the known physical relation of space and time. Each factor suggests some specific hypotheses relevant to human time perception. In perhaps the most salient hypothesis, data already exist that are consistent with the spacetime model; for the other hypotheses, no tests that we know of have been performed.

A Spacetime Processor Would Account for the Compensatory Interplay of Motion and Time: Evidence for the Spacetime Model

One of the most eye-opening predictions of relativity theory is that motion through space and motion through time are compensatory: The more we travel through space, the less we travel through time (see, for example, Greene, 2004; Hawking, 1996, 2001; Hawking & Mlodinow, 2010; Kaku, 2008; Krauss, 2007; Penrose, 2010; Shankar, 2013). At the speeds we normally travel at, this effect on time is not explicitly noticeable; but it is occurring just the same. So if a spacetime processor existed, it would have some kind of exaggerated mechanism for accounting for this interaction. This suggests a straightforward hypothesis for the spacetime processor: That perceptions of motion ought to make time psychologically slow down. Operationally, this means that motion ought to increase estimates of duration (e.g., Cohen, Hansel, & Sylvester, 1953; Goldreich, 2007; Helson & King, 1931), because if time appears to move slower to Observer A than Observer B, Observer A will report that more time has passed in the same interval.

When we go to the literature on time perception, this is—with a couple of exceptions (Chen, Pizzolato, & Cesari, 2013; Orgs, Bestmann, Schuur, & Haggard, 2011)—exactly what scientists have found. Despite the fact that there is a widespread assumption that our time perception mechanisms are fundamentally Newtonian, numerous studies across multiple paradigms have shown that as people perceive motion, time slows down for them (Abe, 1935; Brehmer, 1970; Brown, 1995; Cohen et al., 1953, 1955; Helson, & King, 1931; Jones & Huang, 1982; Kanai & Watanabe, 2006; Kroger-Costa, Machado, & Santos, 2013; Lebensfeld & Wapner, 1968; Masuda, Kimura, Dan, & Wada, 2011; Matthews, 2011; Mauk & Buonomano, 2004; Newman & Lee, 1972; Price-Williams, 1954; Sarrazin, Giraudo, Pailhous, & Bootsa, 2004; Tayama, 2006; Tse, Intrilligator, Rivest, & Cavanagh, 2004; Yamamoto & Miura, 2012). We next provide a summary of this evidence.

Indeed, a long history of research on the well-established kappa effect is consistent with this time-stretching effect of perceived motion (Abe, 1935; Cohen et al., 1953, 1955; Jones & Huang, 1982; Lebensfeld & Wapner, 1968; Masuda et al., 2011; Newman & Lee, 1972; Price-Williams, 1954; Sarrazin et al., 2004). The kappa effect occurs when participants overestimate the amount of time occurring between two repeated stimuli as the physical space between the stimuli becomes larger. The kappa effect thus involves the dependence of temporal judgments on the spatial context; the effect is often directly tied to the phenomenological perception of velocity or motion (see, for example, Jones & Huang, 1982; Masuda et al., 2011), and—consistent with relativity theory—it becomes larger as stimuli move more quickly (Masuda et al., 2011).

Additional studies from different paradigms have investigated how the presence of action for a stimulus affects time duration estimates. For example, Yamamoto and Miura (2012) found that after viewing an image of a person running, participants perceived time to be lengthened—that is, they perceived the presentation duration to be longer—compared with participants who viewed an image devoid of action. Brown (1995) also found that stimulus motion lengthened perceived duration, and further showed that higher velocity stimuli led to increasingly lengthened estimates of perceived time, relative to lower velocity stimuli.

Other work paints a similar picture. Tayama (2006) concluded that increased velocity of motion led to increased estimates of time elapsed. Matthews (2011) investigated the role of velocity by testing whether the time-lengthening effect was equal for objects in constant motion, accelerating objects, and decelerating objects. Viewing objects in constant motion led to the greatest degree of perceived time lengthening. Furthermore, Matthews found that when participants viewed an accelerating object, followed by a stationary object, the result was a perceived lengthening of the duration of the stationary object.

Other studies have explored the effect of the perception of motion by putting participants themselves into motion. Consistent with the spacetime model, Kroger-Costa et al. (2013) found that when a participant is in motion, perception of stimuli duration is lengthened. Decades earlier, Brehmer (1970) found that participants riding in faster moving cars made longer estimates of duration than those in slower moving cars.

In summary, although there exists a small amount of evidence that might be construed as inconsistent with the spacetime model (Chen et al., 2013; Orgs et al., 2011), an overwhelming array of evidence from multiple paradigms is consistent with a model suggesting that humans have mechanisms for processing spacetime in the general direction of relativity theory’s predictions.

Novel Predictions of the Spacetime Processor

All good theoretical perspectives are first and foremost generative (see, for example, Conway & Schaller, 2002). Thus, although it is interesting to note that one of the spacetime model’s key predictions has received empirical validation—and it gives us a good reason to continue pursuing the model—it nonetheless is important to use the model to make future predictions that help us generate new knowledge. Below, we illustrate three additional predictions made by the spacetime model that provide the potential to generate novel findings.

Evidence for the Spacetime Model

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**Novel Prediction 1:** A spacetime processor would account for the magnification of time–motion compensation across large distances. Although much evidence supports that we have a mechanism that in some way accounts for relativity theory’s prediction of the compensatory nature of motion and time, a related (and, in physics, an equally clear and demonstrable) prediction from relativity theory has received no attention at all in the time perception literature. Brian Greene (2004) illustrated by showing that if two observers were 10 billion light years apart, relativity theory shows that Observer A moving a paltry 10 miles an hour toward Observer B would cause Observer A to move 150 years into the future of Observer B! Thus, relativity theory directly shows that the effect of relative motion on time perception ought to be greater the farther the two objects in question are from each other. Although, like all the other spacetime effects observed here, this magnification effect of distance in space is negligible at the small distances we typically travel in, a spacetime processor might nonetheless have an exaggerated mechanism to track it.

This suggests a series of testable hypotheses. For example, one could run typical experiments showing the motion–time perception link while systematically varying the distances between perceiver and perceived object. Furthermore, one can run experiments that systematically vary the distance (or perceived distance) between two objects and their relative motion to each other—Based on the spacetime model, we would predict that as perceived distance increased, the strength of the motion–time perception relationship would increase as well.

**Novel Prediction 2:** A spacetime processor would account for the compensatory interplay of gravity and time. Relativity shows that because gravity bends space, it also bends time. As a result, for objects that are closer to large masses (where gravitational pull would be more immediately present), time moves slower than for objects farther from those masses (see, for example, Hawking, 1996, 2001). A straightforward prediction made by relativity theory, then, is that time moves slower on the earth at low altitudes than at high altitudes, because low altitudes experience more “pull” from the earth’s gravity. And in fact, numerous studies using high-powered, precise atomic clocks have confirmed this effect—One such study showed that time ran faster for clocks that differed in altitude by only 33 inches (Chou, Hume, Rosenberg, & Wineland, 2010). Indeed, the effect is important enough that if satellite global positioning system (GPS) did not account for it, their predictions would sometimes be off by several miles (Hawking, 1996; Hawking & Mlodinow, 2010).

If we have mechanisms for processing time in line with relativity theory, two related psychological hypotheses are suggested by the effect of gravity on time (neither of which has received direct empirical testing to our knowledge). First, and more local to our typical experience, is this: We should perceive time as moving more quickly as we perceive increases in altitude. Objects farther from the earth are higher up, and relativity theory suggests (and empirical observations confirm) that time should move faster at higher altitudes. Thus, as a person perceives increases in altitude, time should psychologically speed up for the spacetime processor. Second, and more generally, we should perceive time as moving more slowly when we perceive that a target is close to a mass that is large on a cosmic scale. Thus, if we perceive that a target is very close to a mass large enough to affect gravity substantially (e.g., an astronaut is close to the sun vs. far away), our spacetime model predicts that time would be dilated for that target.

**Novel Prediction 3:** A spacetime processor would recognize that other people’s experiences of time are different from its own. The thoughtful observer may have noticed that, up to this point, we have conflated the effects of observing alterations that would affect other people’s conception of time and observing alterations that would affect our own conception of time. That is in part because perceptual heuristics and primes often function this way—They often function like direct links tapping into perception mechanisms, and those links sometimes work independent of context. For example, a lot of work on priming shows that subtle exposure to words along specified dimensions directly alters subsequent behavior, even when it makes no conceptual sense based on the context, such as when people walk more slowly after they are exposed to words related to being “old” (for a summary, see Bargh & Chartrand, 1999). In the same way, it is entirely possible that our spacetime mechanisms might be “primed” by images even in circumstances where they would not normally make direct sense, and as such might alter our time perception in the same way that priming “old” alters walking speed. Thus, even if we see other people in motion, or other people close to large gravitational objects, we might show effects of spacetime processing.

On the contrary, one of the more important suggestions of relativity theory is that each observer’s sense of time will differ from every other observer’s sense, based on the principles outlined above. Although spacetime might potentially suggest a number of more speculative hypotheses in this regard—an issue we return to in a later section—one of the more straightforward things we might expect from a spacetime processor is that it would account for the fact that other people’s senses of time might not always be the same as our own. For example, if (a) we have a mechanism for recognizing that objects at different altitudes move through time at different speeds, and (b) Person A recognizes that she is currently at a different altitude from Person B, it follows that (c) Person A would recognize that she and Person B are currently moving through time at different speeds.

General evidence suggests that we adjust for the fact that time “slows down” and “speeds up” across contexts (e.g., Carstensen et al., 1999; Conway, 2004; Droit-Volet et al.,...
ful not only for the direct hypotheses it offers but also for the closely to those known facts drawn from relativity theory. Travel through time at different speeds. The psychological objects with large mass, and that different observers often larger as objects are farther apart, that time slows down near as motion speeds up, that the time dilation effect of motion is physics. Few physicists would disagree that time slows down from consensually agreed-upon implications of classical these hypotheses nonetheless mostly follow fairly directly considering other people’s movement through time. One simple way to test this would be to show pictures/videos of other persons in various conditions where spacetime effects are manipulated, and then ask people to either (a) estimate how much time they think has passed for themselves, or (b) estimate how much time do they think has passed for that person in the picture/video. To the degree that spacetime processing effects are larger for participants’ time estimates for the other people who (in those conditions) would actually be experiencing the effects, this would suggest that we have a mechanism to directly account for the differential effects of spacetime on different targets.

Thus, although we might expect effects of perceived motion and gravity to some degree regardless of context and actor, the spacetime model would expect those effects to be larger when explicitly considering the person(s) to whom the effects should directly affect.

**Additional Implications of Relativity: Speculations Raised by Considering Spacetime**

We have thus far discussed hypotheses that follow in a straightforward fashion from the theory of relativity as classically understood. This generally involves taking empirically validated or theoretically understood findings from the last 100 years of physics—things on which almost all physicists would agree—and extrapolating in a direct way what we might expect a spacetime processor to look like in the human species. While of course, as we have emphasized, no psychological interface with reality is perfectly straightforward, these hypotheses nonetheless mostly follow fairly directly from consensually agreed-upon implications of classical physics. Few physicists would disagree that time slows down as motion speeds up, that the time dilation effect of motion is larger as objects are farther apart, that time slows down near objects with large mass, and that different observers often travel through time at different speeds. The psychological spacetime implications we have drawn thus far correspond closely to those known facts drawn from relativity theory.

However, sometimes a theoretical perspective can be useful not only for the direct hypotheses it offers but also for the speculations and questions it inspires. For example, an evolutionary perspective of cultural transmission has not only generated specific hypotheses, it has also inspired researchers to consider questions about how culture grows that might not have even been asked otherwise (see, for example, Schaller, Conway, & Tanchuk, 2002). Here, we briefly lay out three potential areas of research that are inspired by a consideration of spacetime. These do not directly follow from classic relativity theory, yet they emerge largely because of a consideration of the issues involved with the theory. If relativity theory is a pebble dropped in a pond, these speculations are the outward psychological ripples that emerge from that pebble.

**A Spacetime Processor May Account for the Malleability of Time’s Arrow: Precognition**

Although we generally perceive that time only moves in one direction (from the “past” to the “future”), classic relativity theory shows that there is no reason it cannot move both forward and backward. Unlike in Newtonian physics, relativity theory suggests that space and time are one whole self-contained entity, lumped together as a kind of “frozen river.” This means that, in principle, spacetime implies that time could be bidirectional. In the words of Sheehan (2006), both relativity theory and quantum physics “formally and equally admit time-forward and time-reversed solutions . . . it seems untenable to assert that time-reverse causation (retrocursion) cannot occur, even though it temporarily runs counter to the macroscopic arrow of time” (p. vii).

From a psychological point of view, this asymmetry potentially opens the door for things in the future to affect things in the present. As such, if we had a spacetime processor that accounted for this fact, it would be psychologically possible that things in the future might influence what is psychologically happening right now, in the same way that things in the past influence what is happening right now. This would suggest that the existence of what are sometimes called “psi” phenomena may actually be rooted in both physical and psychological science.

And indeed, recent evidence for precognition offers some reason to believe that this idea of relativity theory might hold some weight. **Precognition** refers to an anticipatory cognitive or affective awareness, conscious or unconscious, of future events. Operationally, it is the influence of future stimuli on one’s present psychological processes. Recent experimental research has demonstrated precognitive effects relevant to reinforcement, priming, habituation, and memory, such that effects operate “backwards in time” (Bem, 2011; Bem, Tressoldi, Rabeyron, & Duggan, 2014; Tressoldi, Lance, & Radin, 2010). For example, Bem (2011), in a package of nine studies published in the *Journal of Personality and Social Psychology*, found that participants were more likely to respond in ways that were later reinforced, when
both the random assignment of reinforcement and the reinforcement itself occurred after the responses in question were already made. In other words, Bem showed that what is about to happen to participants influenced their responses before it happened to them. This surprising finding suggests that current responses were influenced by future reinforcement of those responses, reinforcement for which participants would ostensibly be unaware because it had not “happened” yet. In other, similar studies, participants’ judgments were influenced by primes that occurred after their judgments were reported, and participants performed better on a recall test for words that were rehearsed after the recall test was completed.

These findings have been met with a fair amount of critical skepticism, in part because results have been inconsistently replicable (e.g., see Galak, LeBoeuf, Nelson, Leif, & Simmons, 2012), and more frequently due to both a lack of theoretical explanation and a limited understanding of the potential underlying mechanism(s) of precognitive effects (Bem, 2011). Although we also share a skeptical view in part for these same reasons, it is worth noting that data from a recent meta-analysis of 90 experiments attempting to replicate precognitive effects—using either exact or modified methods outlined in Bem (2011)—provide support overall for the existence of precognition (Bem et al., 2014; for a review of other meta-analytic evidence, see Tressoldi et al., 2010).

Although neither relativity theory nor modern quantum physics directly predicts the specific mechanisms associated with existing precognition effects, classic spacetime theory at the very least offers a theoretical starting point whereby the future might psychologically affect the present. As Bem et al. (2014) discussed, physicists accept that time is both symmetric and asymmetric; it may be that precognition and physics coincide in ways we do not yet understand. As such, precognition fits within the larger framework of relativity theory by suggesting that the direction of time is somewhat malleable at least some of the time.

A Spacetime Processor May Have Time Closely Linked to Entropy

Of course, although relativity theory allows for the possibility of temporal causality to be reversed, this fact raises a bit of a psychological puzzle: Why do we explicitly perceive time moving in only one direction (called “time’s arrow”)? This puzzle only emerges because of relativity’s conception of spacetime; in a commonsense Newtonian framework, we expect time to only move in one direction. Relativity theory thus creates the puzzle of time’s arrow.

So what does modern physics say about the question of time’s arrow? If time can be bidirectional, why do we perceive it to move in only one direction? The most common assumption of modern physics is that this emerges because time and entropy are closely linked. Brian Greene (2004) summed this up:

[T]he only convincing framework we found for explaining time’s arrow was that the early universe had extremely high order, that is extremely low entropy, which set the stage for a future in which entropy got ever larger. (p. 314)

This quote illustrates a commonly accepted physical fact about spacetime: That one of the most fundamental aspects of our experience of time—namely, that it only moves in one direction—is intricately bound to entropy (see also Hawking, 1996; Penrose, 2010). Time’s arrow moves from low entropy to high entropy: If we see a picture of a whole egg and then a picture of the same egg smashed to bits on the floor, we assume that the high-entropy smashed egg came after the low-entropy whole egg.

Although this tie seems fundamental, no research to our knowledge has directly explored this entropy–time perception connection. A consideration of this relationship suggests that, if we have some mechanism that is sensitive to the entropy–time relationship, our time perception might be dramatically affected by “reversing” entropy as it is presented in linear time. So by playing video clips that go from high entropy to low entropy (instead of the reverse)—for example, if one played a clip of billiard balls all “re-assembling” into their typical beginning state on the pool table, rather than the balls moving from that state to becoming more scattered—one might expect that our time perception mechanisms would not function in their normal way. In particular, this could mean that that time slows down because we associate high entropy with the “end” state and, if it is instead at the beginning, are more likely to infer that time must be moving more slowly.

A Spacetime Processor May Have Shared Time Perception Mechanisms

We earlier outlined a straightforward prediction of the spacetime model pertaining to others’ time perception mechanisms—namely, that a spacetime processor would account for the fact that other persons’ time clocks are different from ours in ways conforming to classical relativity theory. However, it is worth noting that, to the degree that we do account for this, it may also have other implications for human psychology. Here, we speculate briefly on what those may be.

Humans are inherently social beings. We have a fundamental desire to belong; we do not want to be permanently alone or outcast; we live by being together (see, for example, Baumeister & Leary, 1995; Conway, Houck, & Gornick, 2014). As a result, it is likely the case that, although we may implicitly account for the fact that other people’s time moves differently from ours, we do not want to be on a different
time continuum than they are. The thought that we are not moving “together” on such a fundamentally basic dimension as time may feel undesirable. This suggests a set of related hypotheses.

One hypothesis is that we may have a mechanism for mentally “synchronizing” our perceptions of time with others, so that we feel like we are, in fact, on the same time plane as they are. And indeed, some evidence suggests that we do have just such an implicit mechanism. In one study (Conway, 2004), participants worked on a task either side-by-side (no interaction) or face-to-face (such that they interacted with others). Participants did not talk about time in any session, yet face-to-face participants showed a tendency to converge in their perceptions of time’s passage, so that their perceptions of time became more like those of their fellow group members (an effect that did not occur in the side-by-side control conditions and was not accounted for by participants’ mood). This research suggests that people seem to have an independent mechanism to implicitly “share” the time perceptions of others they interact with, even when they never talk about that perception directly. This and other findings at the cultural level that suggest cultures have a shared sense of “pace of life” (Conway, Ryder, Tweed, & Sokol, 2001; Levine, 1997) fit in with a spacetime perspective—If, in fact, we do implicitly recognize that others have different time clocks than we do, we may have a compensatory mechanism to reestablish that we belong with them, in the same way that our implicit existential fear of death leads us to have compensatory motivational “buffers” (e.g., Rosenblatt et al., 1989).

A second, related set of hypotheses involves the potential psychological unease caused by feeling one is separate from others on the time dimension. In particular, showing others in higher altitudes than we are or in a motion speeds than the target according to relativity theory (e.g., situations where they would be experiencing different time perceptions of others they interact with, even when they never talk about that perception directly. This and other findings at the cultural level that suggest cultures have a shared sense of “pace of life” (Conway, Ryder, Tweed, & Sokol, 2001; Levine, 1997) fit in with a spacetime perspective—If, in fact, we do implicitly recognize that others have different time clocks than we do, we may have a compensatory mechanism to reestablish that we belong with them, in the same way that our implicit existential fear of death leads us to have compensatory motivational “buffers” (e.g., Rosenblatt et al., 1989).

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Where Would a Spacetime Processing Mechanism Come From?

So far, we have discussed what a potential mechanism for processing spacetime might look like if humans had such a mechanism. We have shown that, in addition to there being reason to believe that space and time are intimately bound in biological substrate in the human brain, there is further already substantial evidence for one of the key predictions of the psychological spacetime model. In addition, there is at least some evidence for two of the speculative hypotheses drawn from the spacetime model.

However, to this point we have spoken loosely of the spacetime processor without consideration of where or how we might have acquired it. Below, we explore three separate reasons why we might process temporal information in a manner consistent with relativity theory: direct adaptations, analogical overlap, and cultural learning.

As Direct Adaptations

It is possible that psychological mechanisms evolved as direct adaptations to spacetime itself. But is this a legitimate possibility? Although, on the surface, we agree with Brian Greene’s opening assessment that there is no necessary survival benefit to perceiving spacetime effects, there are nonetheless good reasons for being skeptical of arguments based on our capacity to perceive the survival value of a psychological mechanism in the distant past (see, for example, Conway, 1999; Conway & Schaller, 2002). We do not fully know or understand the context in which humans emerged, and the relationship of genetics to survival is immensely complex; as a result, it might be premature to assume that a set of mechanisms to more completely assess the nature of spacetime would have conveyed no survival value to its holders.

Equally as importantly, no evolutionary theory suggests that only traits are related to survival last—Many of our existing traits appear to be either “spandrels” or “noise” that serve no necessary survival function (see, for example, Buss, Haselton, Shackelford, Bleske, & Wakefield, 1998; Conway, 1999; Conway & Schaller, 2002). A common example is our bone color, which is likely just an offshoot (a “spandrel”) of other factors relevant to bone density and structure that affect survival—In other words, bone color itself is simply irrelevant to survival (see, for example, Buss et al., 1998). Many of our traits are doubtless like that, and it is possible that we might have developed a mechanism for perceiving spacetime that conveyed no survival value, but it survived as a trait because it did not inhibit gene survival.

Relatively, and more importantly, is the fact that non-Newtonian spacetime effects would seem on the surface to be so small that they would appear to be outside of the human capacity to perceive. As an analog, humans do not appear to have the capacity to see most ultraviolet radiation or to hear sound waves beyond 50,000 Hz. It is perhaps therefore useless to talk about the “interface” of our perception mechanisms with those physical phenomena, because we do not seem to have them at all. So given that the effects of spacetime beyond Newtonian physics would be negligible (often measured in fractions of a nanosecond), it seems unlikely at first blush that we would perceive them at all. The distance between the proposed “exaggerated” mechanisms for human psychology and the reality of spacetime effects in physics seems too great. It is thus a plausible hypothesis that we simply do not have a fine-grained enough temporal mechanism for detecting the effects of spacetime.
at really small units of time, and the psychological spacetime effects that exist occur for different reasons (we explore two other possibilities below).

However, it is also worth noting that a glance at the history of research on time perception suggests a pattern of demonstrating that we can perceive time in progressively smaller and smaller units. Based on what we currently know about temporal-visual-related systems, we can detect stimuli at least on scales of a few dozen milliseconds (Clifford, Holcombe, & Pearson, 2004; Holcombe & Cavanagh, 2001; see Eagleman et al., 2005, for a review; see also Eagleman, 2010; Sadeghi, Pariyadath, Apte, Eagleman, & Cook, 2011). Although this is nowhere near the speeds necessary to detect spacetime fluctuations in our current environment beyond Newtonian levels, as our ability to measure the human mind increases, scientists are discovering faster and faster processing and perception mechanisms. Given the fact that to our knowledge, no concerted scientific effort has been made to discover if such fine-grained levels of spacetime perception are possible, it may be premature to assume that such super-speedy processing mechanisms do not exist; rather, it is possible that we simply have not yet detected them.

As a Metaphorical Analog

Of course, we too feel the same thing that Brian Greene (2004) and others have felt—that it seems unlikely that we have any direct psychological adaptations to spacetime. However, even if that turned out to be true, there are still reasons to believe that we may have perceptual mechanisms that would roughly correspond to relativity theory’s predictions of the relation between space and time. Even when a specific model does not directly apply in perfect correspondence to the observed phenomenon, it can still be beneficial as a rough metaphor (see, for example, Fredrickson, 2013). As such, the consideration of spacetime might in that case still serve as a useful metaphorical analog for how humans process time perception information.

We are not the first to make this suggestion: Others have noted that relativity theory may serve as a useful loose metaphor for understanding the relation of time and motion perception (e.g., Goldreich, 2007; Helson & King, 1931; see Jones & Huang, 1982). Goldreich, for example, uses the relativity-inspired name time dilation to describe the stretching of time during motion—The name is explicitly chosen because of the rough conceptual overlap with relativity theory. However, although these examples highlight that there is clearly empirical reason to believe in the overlap between physical spacetime and psychological spacetime, to date researchers have made little effort to fully explore this conceptual overlap and what it means, or to explore potentially new hypotheses and areas of research that might be opened up by a serious consideration of spacetime.

Generally speaking, the value of co-opting a process from one physical or biological phenomenon to use as a metaphor for helping explain another phenomenon has been seen across multiple areas within psychology. So, for example, although human neural memory networks bear little structural resemblance to traditional computers, computer-based metaphors have led to great advances in our framing and understanding of memory (for a summary, see Solso, MacLin, & MacLin, 2007). Similarly, although cultural systems do not operate under the same processes and constraints as biological evolution, nonetheless the Darwinistic evolutionary metaphor has served to inspire and aid a generation of new research ideas on how culture changes over time (see, for example, Claidière, Scott-Phillips, & Sperber, 2014; Conway & Schaller, 2002, 2007; Gornick, Conway, Cvasa, & Houck, 2013; Mesoudi & Danielson, 2008; Schaller et al., 2002).

Of course, the potential scientific value of pursuing any analog is dependent on having reasons for suspecting that the analog will reflect some underlying reality of the studied phenomenon. In this case, there are at least two potential sets of reasons why there might be overlap. The first set involves empirical considerations: We have already discussed that space and time are clearly linked in the human brain (see, for example, Eagleman et al., 2005) and that one of the key direct predictions of the spacetime model has received empirical support (e.g., Cohen et al., 1953; Jones & Huang, 1982; Kanai & Watanabe, 2006; Kroger-Costa et al., 2013; Masuda et al., 2011; Matthews, 2011; Mauk & Buonomano, 2004; Sarrazin et al., 2004; Tse et al., 2004; Yamamoto & Miura, 2012). Thus, the early returns from the model are promising, offering a number of reasons to believe that some of the other, as yet untested, hypotheses may be worth pursuing.

Second is a variant of the anthropic principle. This principle argues that the things we discover about our universe must in some way be compatible with our conscious processing mechanisms (see, for example, Hawking, 1996). So, for example, with respect to the analogical connection between human memory and computer memory, a view from the anthropic principle would consider that the human mind would not have discovered the possibility of computer storage units if it bore no resemblance to the way we actually process information. Thus, although neurons are nothing like the central processing units (CPUs) in computers, it is perhaps unsurprising that computer memory systems and human memory systems bear some phenomenological overlap. Indeed, it is likely the very reason that we made computer memory systems the way they are—We would be highly unlikely to invent a memory system that was wildly discrepant from our own.

Similarly, the anthropic principle suggests that it is possible that we process information in a spacetime-like way for reasons that are independent entirely of the minutiae of spacetime itself, and yet it is that very fact that allowed us to ultimately discover the more complicated nuances of spacetime to begin with. Although processing spacetime is not
directly intuitively obvious to us, we nonetheless had the capacity to uncover, observe, and understand the way time, motion, gravity, and space all interact. Although this in no way means that we have implicit mechanisms to process spacetime in line with relativity theory, it does at least mean that the ability to understand spacetime was latent within the human species. It is therefore possible that this latent processing ability in fact corresponds to implicit processing mechanisms. This is not a definitive argument for the spacetime model; but it does suggest a reason why we might have an analog spacetime mechanism even if it is not a direct adaptation. The causal arrow for the overlap may, in a sense, go from our spacetime-like mechanisms to our discovery of spacetime, rather than the existence of spacetimecausing us to develop such mechanisms as direct adaptations.

As a Product of Cultural Learning

An overarching knowledge structure may exist in human minds for multiple reasons. It may exist because it reflects some underlying pan-cultural psychological reality, in the way that computer memory reflects aspects of human memory (e.g., Solso et al., 2007). It may also exist because it originates in cultural learning, the way that knowledge structures related to individualism and collectivism are largely learned at the cultural level (e.g., Conway, Clements, & Tweed, 2006; Conway et al., 2014; Conway et al., 2001; Kitayama, Conway, Pietromonaco, Park, & Plaut, 2010; Kitayama, Ishii, Imada, Takemura, & Ramaswamy, 2006).

It is thus possible that relativity theory influences time perception because it provides a conceptual cultural framework for shaping reality (e.g., Conway et al., 2001; Conway & Schaller, 2005; Grob, Little, Wanner, & Wearing, 1996; Kitayama et al., 2010; Levine, 1997), and this learned framework itself has an impact on time perception. The human mind is incredibly malleable to such cultural influences, and as such, it is possible that people learn, for example, about the time–motion integration and compensation for it. If this were the case, the discovery of relativity itself—and subsequent adoption across cultures—would serve as a profound cultural framework for altering the perception of time.

Indeed, other researchers have suggested that time perception is in part a cultural phenomenon (Conway, 2004; Levine, 1997; Zimbardo & Boyd, 2008). Therefore, it is certainly plausible that relativity theory might overlap with time perception because it has become an accepted part of cultural knowledge and, as a result, influences time perception in the same way other deeply accepted cultural folkways influence human psychology. If true, the cultural learning approach to the spacetime metaphor suggests the important idea that as knowledge of relativity becomes more and more pervasive, its spread will correspondingly affect time perception in line with relativity theory.

Do the Potential Origins of a Spacetime Processor Matter?

We have briefly outlined three potential origins of a spacetime processor. But if we have a spacetime processor, would it matter why we acquired it? On the surface, it would seem that all three explanations of why we acquired it would make the same set of predictions.

And that is true in some large sense. However, ultimately, as we gain more and more knowledge of how humans process temporal information, the three different proposed origins would potentially make differing predictions. For example, if we acquired the processor as a direct adaptation to real spacetime selection pressures, the predictions of the spacetime model should be more likely to continue to hold at increasingly smaller units of time—because, in our local pocket of the universe, those smaller increments are the units at which spacetime alterations would actually exist. Conversely, if the spacetime processor emerged because of a metaphorical analog or due to cultural learning, we would be less confident that it would continue to hold at incredibly small levels of temporal analysis. Instead, we might expect that analogs or cultural learning would serve to guide time perception in a general way, only at the kinds of larger units for which we typically make such judgments at a phenomenological level. Thus, evidence that we show spacetime alterations at very small units of analysis would not definitively rule out the analogical or cultural learning origins, but would weigh more heavily in favor of a direct adaptation.

Another potentially important factor on which the models make competing predictions involves cross-cultural replicability. If the spacetime processor has a cultural learning origin, one would expect that the level of knowledge a person or culture had of relativity theory would directly correspond to the predicted time perception effects outlined here. If it proved to be true that the effects outlined here held only for groups of persons with a strong knowledge of relativity, then it would seem increasingly unlikely that the spacetime processor had a direct adaptation or metaphorical analog origin. Rather, that would make a stronger case for a cultural learning origin.

Consider, for example, that the reported effects of time–motion compensation were mostly performed in societies where there likely exists at least a cursory knowledge of the theory of relativity. Although we strongly doubt that most of the participants in these studies were aware of the specific predictions related to the studies in question, it is nonetheless possible that what those studies reflect is not a universal mechanism for accounting for motion–time perception integration, but rather cultural learning of the theory of relativity. If, however, such effects are found to be more or less universal across cultures and independent of the knowledge of relativity theory, this suggests that the spacetime-like effects emerging from this conceptual analysis have some deeper
basis that is more fundamental to the human species (whether of adaptive or analogical origins).

At this point, we do not have enough information to clearly distinguish between these various possible reasons that we might see conceptual and empirical overlap between physical spacetime and psychological spacetime. Like Brian Greene and others, we view a direct adaptation for spacetime processing as fairly unlikely, and thus would expect either the metaphorical analog or cultural learning explanations to be closer to the truth. However, our primary purpose in this article is not to argue for any one potential origin. Rather, it is to point out that there are multiple valid reasons why the overlap between physical spacetime and psychological spacetime may exist. As such, this suggests that it may be worth more fully exploring the psychological spacetime model as an explanatory mechanism for studying time perception.

**Concluding Thoughts**

I had a sneaking suspicion that time was not constant, but I guess I could never prove it. I suppose it didn’t really matter. I even had a theory that time didn’t go in straight line at all. I knew I was no Albert Einstein, but I had the sneaking suspicion that everything that had happened, was happening, or would happen was really happening all the time. There was no past, present, and future. Everything was going on all at once and forever. (Mark A. Roeder)

Our altered understanding of spacetime was perhaps the most important scientific advance of the last century. And yet, in spite of this, its potential implications for human psychology are largely not well understood. The guiding assumption seems to be that we are implicit Newtonians (e.g., Greene, 2004; see also Eagleman, 2004; Jones & Huang, 1982); and because we do not likely have mechanisms to perceive spacetime in a manner consistent with the complicated fashion that it actually exists, we can safely proceed in ignoring psychological spacetime in our study of time perception.

That guiding assumption may end up being right; but existing evidence suggests that it may be at least partially wrong. After all, although we may not—to use Brian Greene’s metaphor that we opened this article with—“feel relativity in our bones,” we nonetheless have the capacity to understand it at some level. Thus, popular author Mark A. Roeder’s “sneaking suspicion that time was not constant” may, after all, turn out to represent something real in human psychology that has yet to be fully explored.

Given that time perception has incredibly important implications for human emotion, life satisfaction, and mental health (e.g., Carstensen et al., 1999; Conway, 2004; Droit-Volet et al., 2011; Droit-Volet & Meck, 2007; Flaherty, 1991; Fredrickson et al., 2000; Gil & Droit-Volet, 2009, 2012; Hawkins et al., 1988; Rowe et al., 2007; Zimbardo & Boyd, 2008), it is vital that we understand it as well as we can. With that goal in mind, the present article at the very least suggests the potential usefulness of considering psychological spacetime as a theoretical and conceptual device. It seems certain that (a) time and space share a lot of biological overlap in the brain, (b) we do at least in some way account for the relationship of motion to time in a manner consistent with relativity theory, (c) some speculative hypotheses consistent with the spacetime model have received support, and (d) there are additional conceptual reasons to think that relationship might apply across numerous other areas of time perception. Thus, more fully considering the overlap between physical spacetime and psychological spacetime might prove to bear fruit in our quest to better understand time perception.

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**Notes**

1. The present article discusses possible evolutionary processes from the lens of evolutionary psychology, but it does not necessarily assume a direct evolved adaptive mechanism. We return to this issue later in the article.
2. The Chen, Pizzolato, and Cesari (2013) study involved elite athletes rating time intervals following viewing action versus nonaction pictures. Viewing action pictures compressed (rather than dilated) time. However, this study did not involve the perception of actual (only implied) motion and was with a very select population. The Orgs, Bestmann, Schuur, and Haggard (2011) study involved apparent motion based on the timing of pictures of postures in different positions, and they found that increased perceived movement in that scenario compressed time perception. Even if one accepts both studies as direct evidence (and it is unclear whether the Chen et al. study is directly related), most real effects generally have counterexamples, and the overwhelming balance of evidence is in support of the time dilation hypothesis derived from the proposed model.

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