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Thinking in and about time: A dual systems perspective on temporal cognition

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Abstract

We outline a dual systems approach to temporal cognition, which distinguishes between two cognitive systems for dealing with how things unfold over time – a *temporal updating system* and a *temporal reasoning system* – of which the former is both phylogenetically and ontogenetically more primitive than the latter, and which are at work alongside each other in adult human cognition. We describe the main features of each of the two systems, the types of behavior the more primitive temporal updating system can support, and the respects in which it is more limited than the temporal reasoning system. We then use the distinction between the two systems to interpret findings in comparative and developmental psychology, arguing that animals operate only with a temporal updating system and that children start out doing so too, before gradually becoming capable of thinking and reasoning about time. After this, we turn to adult human cognition and suggest that our account can also shed light on a specific feature of humans' everyday thinking about time that has been the subject of debate in the philosophy of time, which consists in a tendency to think about the nature of time itself in a way that appears ultimately self-contradictory. We conclude by considering the topic of intertemporal choice, and argue that drawing the distinction between temporal updating and temporal reasoning is also useful in the context of characterizing two distinct mechanisms for delaying gratification.

Is temporal cognition a basic, primitive ingredient in mental life or is it a complex achievement requiring a great deal of cognitive sophistication? On the one hand, humans and animals are by necessity adept at timing their actions appropriately, at ensuring that sequences of actions unfold in the correct order, and at keeping track of changes in the environment that occur with temporal regularity. In that sense, both people and animals are inherently temporal creatures. On the other hand, the nature of time remains the subject of highly technical debates among metaphysicians and theoretical physicists (Bardon 2013; Carroll 2010), and different cultures have different systems for marking time, acquiring which requires explicit teaching and occurs over a protracted period of development (Aveni 1990; Friedman 1982; McCormack 2015). In these respects, thinking about time is something that seems very difficult.

It is by no means obvious that being able to think about time is something that is ontogenetically or phylogenetically primitive, despite animals' and infants' prowess at processing a variety of types of temporal information. The idea that animals are cognitively "stuck in time" has a long-standing history (Aristotle 1984; Bergson 1911), and has been the subject of a considerable amount of research (for discussion, see Clayton et al. 2003a; Roberts 2002; Suddendorf & Corballis 2007a; Zentall 2005). Despite convincing evidence that animals can retain information about things that they have experienced in the past (e.g., Babb & Crystal 2006; Clayton & Dickinson 1998; Eacott et al. 2005), and act in ways that prepare them for situations that are yet to come (e.g., Mulcahy & Call 2006; Osvath & Osvath 2008; Raby et al. 2007), there is still widespread disagreement about how to interpret this evidence. Similarly, the idea that children have limited ability to think and reason about time has a long-standing history (Fraisse 1964; Piaget 1969). Infants can process a variety of types of temporal information even from birth (e.g., de Hevia et al. 2014), toddlers are adept at learning about event order (Bauer et al. 1998), and the use of tense in language typically appears very early (Weist 1989). Nevertheless, as we shall discuss, there are good reasons to believe that it takes several years before children can think about time as adults do.

In this article we outline a *dual systems* approach to temporal cognition and argue that it is useful not just for framing issues in comparative and developmental psychology but also in considering aspects of adult human cognition. We recognize that there is considerable debate about how the claims of such accounts should be interpreted, in particular whether it might be more appropriate to refer to dual processes rather than dual systems (Evans & Stanovich 2013). We will not address these debates here, but instead identify four key claims that provide the basis for conceptualizing the distinction we want to make as a distinction between two systems: We claim (i) that one of these systems is less ontogenetically and phylogenetically primitive than the other, (ii) that one depends on experience and learning in a way the other does not, (iii) that one typically involves more cognitively effortful reasoning than the other, and (iv) that they co-exist and can potentially be in conflict, yielding contradictory beliefs or judgments. This set of claims is similar to sets of claims made in the context of other "dual systems" accounts (Kahneman 2011; Sloman 1996; Smith & DeCoster 2000), and for this reason we believe it is useful to adopt the same terminology. Note, however, that in distinguishing between two systems we are not claiming that they have distinct and discrete neurological bases or operate entirely independently, and we acknowledge that there may be other ways of describing the distinction we make (e.g., as two sets of processes).

Our dual systems approach to temporal cognition distinguishes between a *temporal updating* system and a *temporal reasoning* system. Abilities that have been studied under the heading of temporal cognition include a sensitivity to temporal duration, a sensitivity to repeating temporal periods, ways of keeping track of temporal order, and the ability to judge where in time events are located. What these diverse abilities have in common is that they are all used to solve tasks that involve things unfolding over time in a certain way. Such tasks may differ in ways that mean that they each require a somewhat different explanation of performance, for instance because they involve different timescales (e.g., seconds versus years), or because they require a sensitivity to duration rather than succession. The distinction between temporal updating and temporal reasoning is intended as a more fundamental distinction that cuts across these differences. There is a basic reason why we want to make this distinction: We believe that there are a number of different tasks that involve things unfolding over time in a certain way that can be solved without the ability to represent and reason about time itself. The temporal updating system is sufficient to solve such tasks, whereas other tasks require the temporal reasoning system. We will first provide an outline characterization of each of the two systems and describe the types of behavior that the more primitive temporal updating system can support, but also describe its limitations. After this, we will use the distinction to interpret findings from the comparative and developmental literatures. To anticipate, we will argue that neither animals nor infants can think and reason about time – they rely entirely on the temporal updating system, although in the case of children there is also an important developmental story to be told about the emergence of the temporal reasoning system. We will then turn to adult temporal cognition and suggest that our account can also shed light on a specific feature of adults' everyday thinking about time that has been the subject of debate in the philosophy of time. We will conclude by considering the phenomenon of intertemporal choice and outlining a way in which the distinction between temporal updating and temporal reasoning bears on existing discussions of that phenomenon too.

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1. The two systems

1.1. Temporal updating

A creature capable of what we call temporal updating maintains a representation of how things are in its environment, which can be conceived of as map-like in so far as it contains information about locations, but which can also contain information about the existence of objects, and features of those objects, while leaving the location of those objects underdetermined. As things change over time, the creature will receive new information, and this information may contradict an aspect of its existing representation. But all the creature does in response to receiving such information, using the updating system, is change the relevant aspect of its representation of the environment. That is to say, crucial to the temporal updating system is that it deals with changing input by *changing representations*, rather than by *representing change*. If a change happens, it simply records the new, changed state of affairs, rather than also representing that things were previously different from how they are now. Thus, the temporal updating system operates with a model of the world that concerns the world only ever as it is at present. Other times, and how things are at other times, are not represented in the model at all.

We should stress that when we say that the model of the world used in temporal updating is a model that concerns the world only as it is at present, this is compatible with it being based on information the creature has gathered over time. It can therefore also include information about features of the world that are currently outside the creature's sensory scope, but which the creature has learned about – that is, about features of locations it does not currently occupy, or about the existence of certain objects. There is even a sense in which this provides for a primitive way of representing goal states: The creature can think of certain items represented as existing in its environment as desirable, and of certain locations in that environment as good locations for doing certain things, and it can respond to these opportunities its environment might afford. This would allow it to act in ways that de facto prepare it for future encounters with those items or locations, even though other times are not represented in its model of the world as such.

In order for the temporal updating system to work, the creature's model of the world has to maintain information over time and also update as new information is received. This updating will result in changes to the creature's world model; these include changes about, for example, what objects are at which locations, but also about what is or is not desirable or what the right thing to do is at certain places. Thus, some updating will happen as a result of changes that occur in the creature's environment, independent of the creature itself, but some will happen because of changes in the creature's motivational state (we discuss an example of the latter in sect. 2.3). Certain parameters will govern these maintenance and updating processes, and we assume that these parameters will vary considerably in a context- or task-dependent way. For example, some types of information may be maintained for only very short periods of time and quickly lost or updated, consistent with the idea of the contents of a working memory store changing dynamically, whereas others might be maintained for lengthy periods and be resistant to change. The types of mechanisms involved in making updates to the creature's model of the world in response to changes purely extrinsic to the creature are also likely to be quite different from those involved when the changes are changes in the animals' motivational state. What these mechanisms are, though, and what parameters govern their operations are empirical questions, and none of the arguments given below require making any particular assumptions about them, other than the basic assumption that information about objects and locations can be maintained even when they do not remain within sensory range.

1.2. Temporal updating and behavior

What follows is a description of some of the behaviors that we believe the temporal updating system can support. In each instance, we also specify what we take to be the related limitation, that is, what a creature cannot do if it is operating only with a temporal updating system.

(i) **Single-trial learning.** A creature capable only of temporal updating can acquire new information about the world from even a single learning episode and change its model of the world accordingly. This information can be of a variety of types, combined in various ways (e.g., information about the spatial location and nature of an object), and it can be held in memory without the creature continuously making use of it (e.g., it might only do so at a later occasion after being cued). **Limitation.** Making use of information acquired in the past, even if it stems from just one learning episode, is separate from and does not require representing that information as stemming from the past, which is something a creature capable only of temporal updating cannot do.

(ii) **Elapsed-time sensitivity.** A creature capable only of temporal updating can nevertheless be sensitive to how much time has elapsed since a certain event happened. Aspects of its model of the world might have a "shelf life." That is, after incorporating a new piece of information of a certain type into its representation of the world (e.g., where some food is located), it might then only store that information for a certain amount of time and as a result its representation will change yet again at a later point in time. This could be governed systematically by an interval timer. Once a certain amount of time has elapsed on such a timer, the creature would no longer operate with a model of the world that includes the relevant piece of information (see sect. 2.1 for more detail). **Limitation.** There is no sense in which the creature needs to be representing how long ago it obtained the relevant piece of information, the representation of which is governed by a timer. This piece of information simply is or is not included in the creature's model of the world as a function of how long ago it was obtained.

(iii) **Sequential learning.** The type of sensitivity to elapsed time we have just characterized involves a process governing what happens to elements of a creature's model of the world over time, without temporal relations being represented within the model itself. Similar processes might also explain certain basic forms of sequential learning. A creature might become sensitive to the temporal order in which certain kinds of sequences unfold by acquiring a routine for updating its model of the world in that order, rather than that order being represented in the model itself. **Limitation.** A signature limit of the temporal updating system is that the correct functioning of the system depends on the creature receiving information about changes in its environment in the same order in which those changes happen; it will produce errors in situations in which these two orders come apart.

(iv) **Anticipation.** We can distinguish at least two ways in which such a creature might produce behaviors that serve to prepare for future states of affairs. First, the creature may possess some sort of temporal sensitivity whereby it behaves in a certain way when a phase timing system is in a certain state (e.g., turning up at a certain location at a certain time of the day), thus enabling it to behave in a way that yields future benefits. Second, as we said, such a creature may have a primitive way of representing goal states, by representing items existing in its environment as desirable, or locations in that environment as good locations to do certain things. This may cause it to act in ways that are optimal given certain possibilities its environment may afford (discussed further in sect. 2.2). **Limitation.** If they are not immediately accessible, the items represented as desirable (or the locations represented as good locations to do certain things) will de facto, at best, be encountered by the creature at some point in the future. However, the creature can represent these items (and locations), and respond to their presence in its environment, without having the means to represent its potential encounters with them as events occurring at a separate, future point in time.

1.3. Temporal reasoning

The key difference between a creature capable only of temporal updating and one that is able to engage in what we call temporal reasoning is that the latter operates with a model of the world that includes a temporal dimension. That is to say, the model contains addresses for different points in time, and can therefore contain information not just concerning the world as it is at present, but also information about states of affairs different from those existing in the present, which existed in the past or will exist in the future. Here we summarize what we take to be the most fundamental kinds of representational resources this involves.

(i) **Representing particular times:** A creature capable of temporal reasoning can represent events as happening at particular times, each of which only comes round once. Creatures not capable of temporal reasoning, by contrast, while capable of becoming sensitive to repeated temporal patterns in their environment (e.g., processes that display a circadian rhythm), will not distinguish between individual instantiations of these patterns as distinct unique occurrences (Campbell 1996).

(ii) **Representing temporal order.** Because a creature capable of temporal reasoning can represent the temporal order relations between events happening at different times, it can use information about this order to arrive at a correct model of the world. It is not restricted to arriving at a correct model of the world only if it receives information about changes in its environment in the same order in which those changes occur.

(iii) **Tense.** A creature engaging in temporal reasoning is also capable of using the system of particular times as a framework for orienting itself in, by using *tense*, that is, locating events in the past, present, or future. By contrast, the representations entertained by a creature capable only of temporal updating are tenseless, or untensed. Its model of the world concerns the world as it is at present, not because items in it are represented *as present*, but simply because it is the model entertained at present.

Having briefly outlined some of the key features of both the temporal updating system and of temporal reasoning, we will turn to considering ways in which the distinction between these two systems might be relevant to the interpretation of existing empirical research. Before doing so, we add two brief clarificatory comments.

First, we assume the existence of particular timing mechanisms, which can explain how even a creature capable only of temporal updating might nevertheless display forms of behavior that are sensitive to elapsed time. Timing mechanisms of some sort are widely assumed to be available even to basic creatures (e.g., insects, Bradshaw & Holzapfel 2010); we remain neutral on their nature (see Grondin 2010). Clearly, there are important further questions about the precise ways in which these mechanisms operate, and the limitations they are subject to. It is important to note, however, that our suggestion is not that there is one form of cognition – temporal updating – that relies on the existence of mechanisms of this type, and another one – temporal reasoning – that does not. Mechanisms keeping track of time can obviously also be involved in contexts in which individuals make explicit judgments, for instance, about how long ago a certain event occurred (Friedman 2001). The issue at stake concerns the function the relevant mechanisms play as part of the two systems: In one case, they simply govern the updating and maintenance of elements of the creature's model of its present environment; in the other, they ground a representation of a temporal interval extending into the past (see sect. 2.1).

Second, as we characterize it, the difference between temporal updating and temporal reasoning is fundamentally concerned with what a creature can represent – that is, whether or not its model of the world contains a temporal dimension. In characterizing the distinction in this way, we have assumed that not all of the ways in which a creature might be sensitive to aspects of its environment involve that creature actually representing those aspects. That is, we are operating with a notion of representation that distinguishes representing an aspect of the world from simply being sensitive to it (see also Peacocke 2017). This has to be distinguished from a broader notion of representation such as that involved when lower-level brain mechanisms are described as operating on "representations" (e.g., one might describe the early visual system as "representing" the differences between the two retinal images, but this is clearly not part of what is visually represented in the viewer's perception). There has been considerable debate on how exactly to characterize the relevant difference between these different notions of representation (for some influential early discussions, see Dennett 1969; Stich 1978). For present purposes, we want to emphasize that the distinction we are drawing between merely being sensitive to temporal features of the world and representing time is not just a terminological one. If a creature can do the former but not the latter, this has concrete behavioral implications. For example, as we have explained, the correct functioning of the temporal updating system is dependent on the creature receiving information about changes in its environment in the order in which these changes happen. This is a signature limit of the temporal updating system that the temporal reasoning system is not subject to (see sect. 3.1 for further discussion).

2. Are animals capable of temporal reasoning?

One type of debate that might be reframed by adopting the approach we are advocating is the debate about the existence of capacities for "mental time travel" (MTT) in non-human animals. Though this issue has received a great deal of attention (Roberts 2002; Suddendorf & Corballis 2007a; Zentall 2005), existing debates have reached something of an impasse, arguably because of the way in which some researchers have framed the basic dialectic. One strand of debate has considered whether MTT should be defined in information processing terms or in terms of a particular kind of conscious awareness (Clayton et al. 2003a; Tulving 2005). Yet, if the issue is entirely about possessing a type of conscious awareness, the question of whether animals are capable of MTT becomes empirically intractable. Similarly, researchers disputing the existence of MTT capacities in animals often appeal to the operation of low-level associative mechanisms that might be sufficient to explain the relevant behavior in each case (e.g., Redshaw et al. 2017; Suddendorf & Corballis 2010). Yet, while such alternative explanations might in principle be available in each case, dealing with individual findings in this sort of ad hoc way seems unconvincing.

We believe that the distinction that we are drawing, between temporal reasoning and temporal updating, provides a more helpful alternative to the dichotomies in play in these existing debates. Our distinction is one between two different systems of cognition, rather than one between cognition and mere low-level association. In describing animals as capable of temporal updating only, we assume that it nevertheless makes sense to talk about them as operating with a model of the world, and indeed a model that represents objects or places currently outside their sensory scope. We now discuss three empirical paradigms that have been used to make the case for MTT abilities in animals, and explain how animals might show the types of behavior in question even if they are restricted to mere temporal updating. We have chosen these paradigms because they are generally regarded as making the strongest empirical case for MTT capacities in animals. Some of them have been tested on more than one species, but only corvids have so far been shown to be successful in all three of them. We therefore concentrate on the relevant studies with corvids. Since our argument is that these studies are not able to establish whether animals are capable of temporal reasoning rather than just temporal updating, we will also consider later (sect. 3.3) what sort of alternative empirical paradigms, not yet tested on animals, would be able to establish this.

2.1. "What-when-where" memory

The most influential paradigm that has been taken to measure MTT to the past in animals is that of Clayton and Dickinson

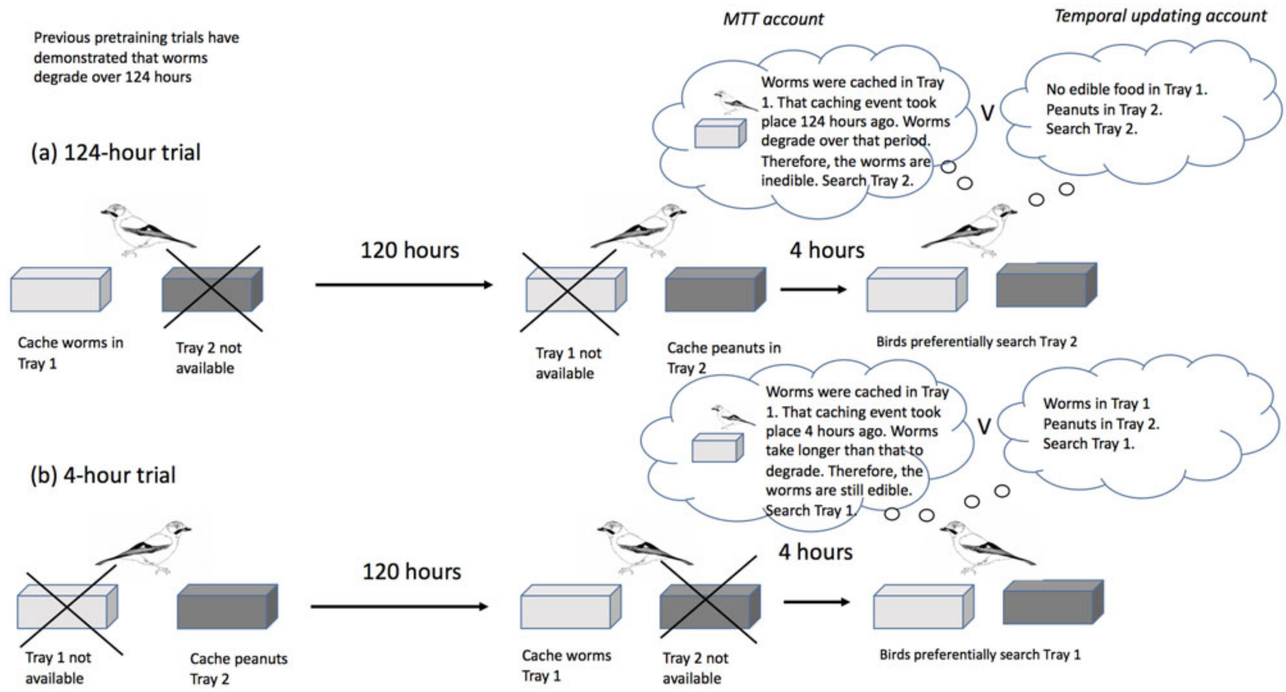

Figure 1. Illustration of test trials in Clayton and Dickinson's (1998) study. In (a) 124-hour trials, scrub jays cached worms in Tray 1 and peanuts 120 hours later in Tray 2. After another 4 hours, they were allowed search in both trays. In (b) 4-hour trials, the birds initially cached peanuts in one tray and then cached worms in another tray after a 120-hour delay; 4 hours later they were allowed to search in both trays. Worms are the birds' preferred food, but birds in the Degrade condition of the study received a series of pre-training trials in which they learned that worms had degraded after a 124-hour period. These birds preferentially searched for peanuts in 124-hour trials and worms in 4-hour trials. The figure contrasts the type of representation assumed to underpin the birds' preferences according to an MTT account with that which is assumed by the temporal updating account. On the former account, the representations have tensed content that leads birds to infer that the worms are not edible. On the latter account, it is assumed that whether the birds' model of the world continues to include a representation of edible worms in Tray 1 is governed by an interval timer.

(1998). These researchers aimed to demonstrate that scrub jays can remember three key pieces of information about past events: what happened, where it happened, and when it happened. For present purposes, it is the last of these pieces of information that is crucial. Representing that something happened at a particular point in the past is an instance of temporal reasoning. We therefore need to ask whether these studies provide good evidence that animals can do so.

In the original study, what was taken as evidence that birds can remember "when" information was the fact that whether or not they returned to a cache site was appropriately delay-dependent. As shown in Figure 1, birds that learned that worms degraded over a period of 124 hours did not return to a cache of worms if given access to it after a 124-hour delay, but instead returned to a cache of non-degrading peanuts. By contrast, if the delay was just 4 hours, birds returned to the cache of worms (their preferred foodstuff) rather than the peanuts (see also Clayton et al. 2003b). To think that this study measures MTT is to think that the birds can remember the event of caching the worms, and how long ago this caching event occurred (Salwiczek et al. 2010). Our claim is that there is no need to make such an assumption in order to explain the birds' behavior. It could be that the birds have some form of interval timing mechanism that governs how long the representation of edible worms remains a part of their model of the world (McCormack 2001). Such a timer would begin to operate at the time of caching, and if the worms are then found to be rotten upon retrieval after a given interval (as in the learning phase of this study), the timer will subsequently ensure that a caching site is no longer represented as containing edible worms once that interval has elapsed (see Figure 1). In that way, we need not assume that the birds can remember the caching event itself; they simply do or do not continue to represent the hidden worms as a function of the state of their internal timer. Notably, this is quite different from assuming gradual forgetting of the locations of cached foodstuffs, although one could potentially describe it as a form of interval-timer controlled forgetting. Characterized in this way, what is distinctive about this type of forgetting is that it is appropriately flexible to the interval in question.

There are obviously further questions to be asked as to how exactly such an interval timing mechanism, which is triggered by the initial caching event, might function. Studies of interval timing in animals typically use considerably shorter intervals. Indeed, Buhusi and Meck (2005) define interval timing as covering the range from under a second to 24 hours. However, there is no reason in principle to assume that animals do not have timing mechanisms that would allow them to be sensitive to the length of a 124-hour period (or even longer). Certainly, we are not committed to the idea that such a mechanism need be a dedicated internal clock; for example, a mechanism that keeps track of how many (fractions of) circadian cycles have passed would also be sufficient. Moreover, it is not just our account that needs to postulate the existence of such a mechanism that keeps track of time. Any account that holds that the birds actually remember the caching event and how long ago it occurred must also assume the existence of a mechanism that allows them to make an accurate judgment about the distance in the past at which that event occurred.

Clayton et al. (2003b) explicitly consider, and do not reject, the possibility that the scrub jays' search behavior in their task could be governed by some interval timing mechanism, even in the case of somewhat more complex experimental designs. However, they do not seem to believe that this has a bearing on whether the task can be taken to measure MTT to the past. Our argument is that such a mechanism would allow animals to show the appropriate level of temporal sensitivity in the absence of any capacity to represent past events, by facilitating temporal updating in a way that is delay-sensitive. The crucial point is that in order for the timing mechanism to fulfill its purpose, it is enough for it to govern what happens to elements of the animal's model of its current environment; we need not postulate any ability to represent other times within this model (see also Hoerl 2008).

2.2. "Mental time travel to the future"

We now turn to considering whether a temporal updating account can also explain animal behavior in studies purporting to measure MTT to the future. Two types of tasks have been used in this area: tasks involving tool saving (inspired by Tulving's 2005 original "Spoon test"; Dufour & Sterck 2008; Mulcahy & Call 2006; Osvath & Osvath 2008) and tasks involving animals caching food that they do not currently desire eating (Correia et al. 2007; Cheke & Clayton 2012). We will consider each in turn.

2.2.1. Tool-saving tasks

A study by Kabadayi and Osvath (2017) can serve to illustrate the general structure of the tool-saving tasks. In this study, ravens first learned that a certain tool – a stone – could open an apparatus containing a food reward (see Figure 2). The following day, they were re-introduced to the baited apparatus, but now the tool to open it was not available, and the apparatus was removed after a while. One hour later, and at a different location, the ravens were offered a forced choice selection between the functional tool and three non-functional distractors. Fifteen minutes after that, they were re-introduced to the apparatus. Kabadayi and Osvath found that the ravens selected the functional tool on the first test trial of this kind, and that they did so also on the majority of further trials, on which they had to make their selection 15 minutes before being given access to the apparatus.

Does success in this tool-saving task require temporal reasoning, or can it be achieved using only the more basic temporal updating system? As we said before, an animal capable only of temporal updating maintains a model of the world only as it is at present. However, we allowed that this model could include items that the animal currently has no perceptual access to. Even if the ravens are capable only of temporal updating, the apparatus is still likely to figure in their model of the world when they are presented with the tool and the distractors, since they have learned about its existence. Upon being re-introduced to the tool, the birds might therefore realize that this gives them the potential opportunity to open the apparatus, and this might be enough to motivate them to select the tool. That is to say, they select the tool because they want to open the apparatus, which they think of as part of their current environment.

Kabadayi and Osvath (2017) say that their study "suggests that ravens make decisions for futures outside their current sensory contexts" (p. 203). It is important, however, to distinguish between at least two ways in which this claim might be interpreted. As indicated, we agree that the birds' behavior takes account of an *object* not currently within their sensory scope. As it is not within their current sensory scope, it is also true that they will therefore have access to that object only after a

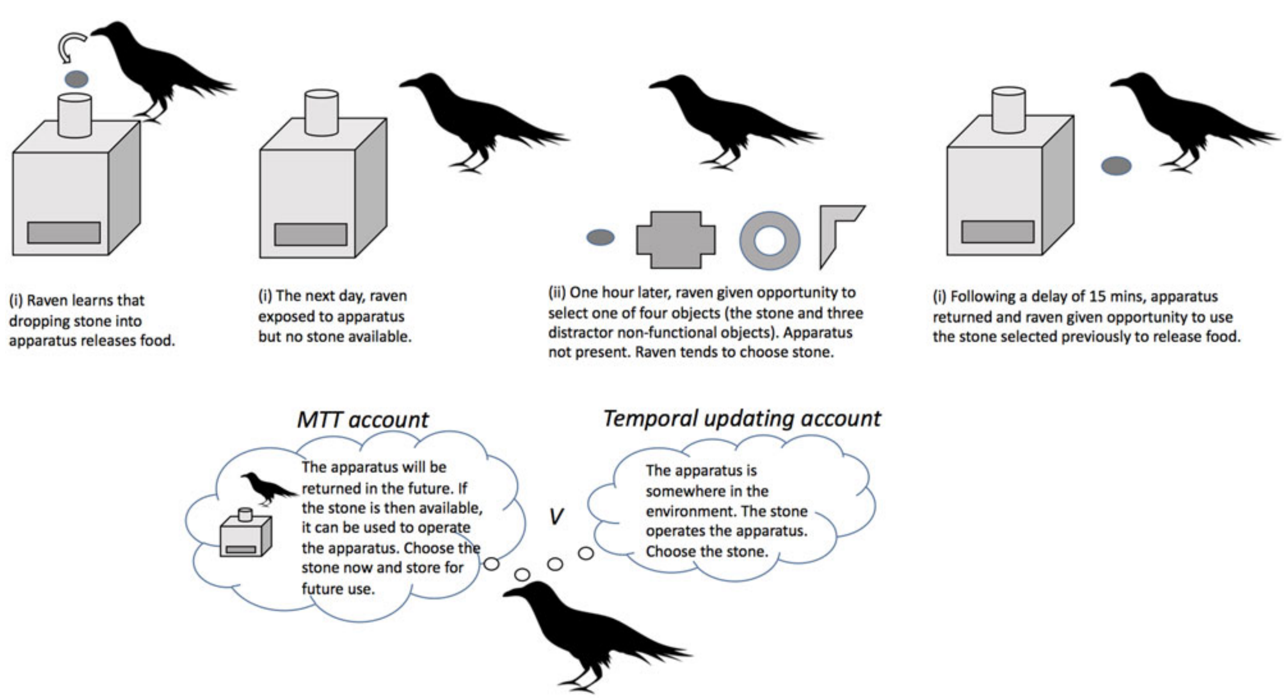

Figure 2. Illustration of the tool-saving procedure in Kabadyi and Osvath's (2017) study, in which ravens preferentially select a stone that can be used to operate an apparatus to release food (Only part of the study carried out by Kabadyi and Osvath is described here). The figure contrasts the type of representation assumed to underpin the ravens' performance according to an MTT account with that which is assumed by the temporal updating account. On an MTT account, birds infer the need for the tool by representing a future event in which they will re-encounter the apparatus. On a temporal updating account, the birds' behavior is governed by a representation that includes information about objects outside of their current sensory scope (the apparatus) but does not include tensed content.

delay (if at all). Nevertheless, it does not follow from this that, in acting on the basis of their representation of this object and its properties, the ravens must also be representing their future encounter with that object as such, as happening at a separate point in time distinct from the present. It is true that the experiments in question de facto involve a delay between the time when the tool is selected and the time when it can be used. But it is far from obvious that this delay plays any role in the reasoning that leads the birds to choose the tool. (It is interesting to note, in this context, that the birds chose the functional tool already on the first test trial, before they had any opportunity to learn that they would be re-introduced to the apparatus a set delay after tool choice.)

Part of what might motivate the idea that tool-saving behavior demonstrates temporal reasoning capacities is that it seems to require some form of grasp of potential opportunities the environment might afford. But there is a more demanding and a less demanding way of understanding what the latter involves. In a different context Osvath and Osvath (2008, p. 662) describe planning in humans as involving "a capacity to construct mental experiences of potential events, something that could be expressed as a projection of the self into possible future events." To think of the ravens as engaging in planning in this sense would be to ascribe to them a capacity to represent modalities themselves – the ability to represent the future time of being confronted with the apparatus as a point in time distinct from the present at which two possible states of affairs could obtain – the animal having the functional tool or not having it – depending on what the animal does now. What we are arguing is that success in tool-saving tasks does not necessarily require a grasp of possibility in this sense (for a study suggesting that non-human primates are in fact unable to represent such dual possibilities, see Redshaw & Suddendorf 2016). It requires a grasp of possibility only in the more basic sense of requiring a grasp of the apparatus as an object that is potentially accessible, even though it is not within the animal's sensory scope. Such a grasp can be grounded in a representation simply of how the world actually is now (e.g., "there is a baited apparatus that can be opened with this tool"), albeit one that might leave some aspects of states of affairs in that world underdetermined. More specifically, it can be grounded in a representation of the form we take to be involved in the temporal updating system – a representation on which the object is represented as existing somewhere in the birds' current spatial environment, and in this sense as potentially accessible. Together with the motivational state of desiring the contents of the apparatus, this seems sufficient to explain why the birds choose the tool.

2.2.2. Caching tasks

To illustrate the second type of task that has been taken as evidence of future MTT in animals, we will describe the study by Cheke and Clayton (2012). This study, depicted in Figure 3, relies

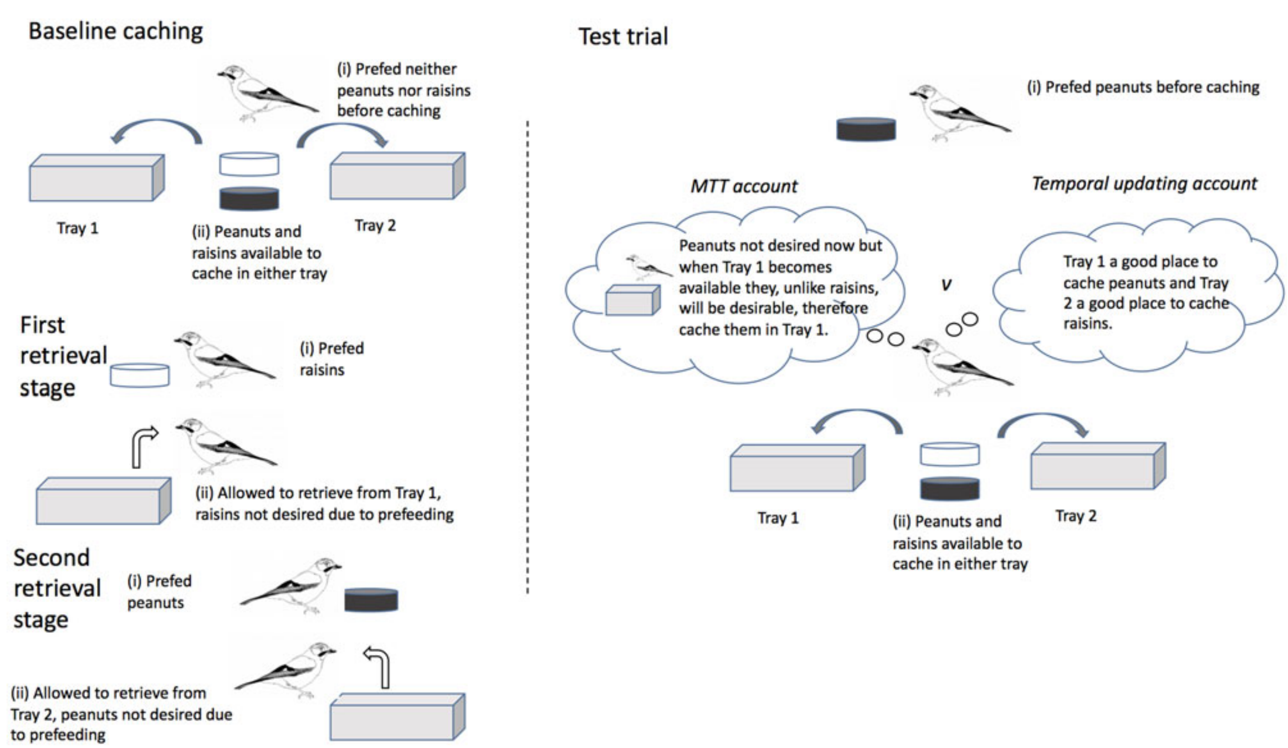

Figure 3. Illustration of the procedure in Cheke and Clayton's (2012) study for one pair of food types (peanuts and raisins). Boxes represent trays made available as caching locations; discs represent containers with food – black for peanuts, white for raisins. In the initial phase of the study (left-hand side of the figure), the birds were allowed to freely cache peanuts and raisins in two trays. In this initial phase, birds had not been pre-fed either food type. After a delay, they were pre-fed raisins and then allowed to retrieve from Tray 1. The pre-feeding of raisins meant that they no longer desired the raisins in the tray, preferring the peanuts. After a second delay, they were pre-fed peanuts and allowed to retrieve from Tray 2. The pre-feeding of peanuts meant that they no longer desired the peanuts in the tray, preferring the raisins. In the subsequent test trial (right-hand side of the figure), the birds were first pre-fed peanuts and were then again allowed to freely cache raisins and peanuts in both trays. The birds now preferred to cache peanuts in Tray 1 and raisins in Tray 2. On an MTT account, the birds infer that they should cache peanuts in Tray 1 on the basis of a representation of a future event in which they will find peanuts but not raisins desirable. On a temporal updating account, it is assumed that the birds update their model of the world, learning during the two retrieval stages that Tray 1 is a good place to cache peanuts and Tray 2 is a good place to cache raisins.

on the fact that the birds show specific satiety effects; that is, if they are sated on one food type, they prefer to eat a different food (note the specific set of foods used varied between birds; we illustrate one example set, and also only part of the overall study). This study started with a baseline caching trial in which birds were pre-fed with their maintenance diet that did not include peanuts or raisins, and then given the opportunity to cache each of the latter two food types freely in two trays. This was followed, after a delay, by a first retrieval stage in which they were pre-fed raisins and subsequently given access to Tray 1 only. After a further delay there was a second retrieval stage in which they were pre-fed peanuts and subsequently given access to Tray 2 only. In the test trials, which occurred some time after these retrieval stages, birds were pre-fed peanuts and then again allowed to cache both raisins and peanuts freely in the two trays. Of interest was whether the birds would cache the two foodstuffs in a manner that corresponded to which food they would prefer to retrieve from which tray, given their specific satiety at retrieval from the relevant tray. Would they cache peanuts in Tray 1, because they will be sated on raisins when Tray 1 becomes available, and would they cache raisins in Tray 2, because they will be sated on peanuts when Tray 2 becomes available? In fact, three out of four birds showed this pattern.

Cheke and Clayton's (2012) discussion frames this finding in terms of the idea that animals can "act for a future need that is different from their current one" (p. 171), or "overcome their current desire to anticipate … future needs" (p. 171), implying that it demonstrates MTT capacities. As we will argue, though, this is a somewhat misleading characterization, and an explanation of the birds' behavior purely in terms of temporal updating is readily available. According to this alternative explanation, birds will, under normal circumstances, represent both caching trays as equally good locations for caching food. This is what happens in the baseline caching trials, in which they cache foods in equal amounts in both trays. The birds are then given the opportunity, in the two retrieval stages, to retrieve food from Tray 1 only when pre-fed raisins and from Tray 2 only when pre-fed peanuts. In response to this, we suggest, they update their model of the world, such that now Tray 1 is represented as a good location for peanuts but not raisins, whereas Tray 2 is represented as a good location for raisins but not peanuts. This change in their model of the world explains why they subsequently differentially cache each foodstuff in a different location.

One might object that this explanation leaves out the significance of the fact that the birds are pre-fed peanuts at the start of the test trial and are thus, when subsequently allowed to cache, already sated on this food. Despite this satiation, they nevertheless cache peanuts in Tray 1. This seems to be what is behind Cheke and Clayton's (2012) claims about the birds overcoming their current desires in favor of future ones, which suggest an argument along the following lines: The birds are currently sated on peanuts. Yet, they cache peanuts in the tray that will become available after they have been pre-fed raisins. Thus, they must be able to realize that, at that future time, they will desire to eat peanuts, rather than raisins, and this is what motivates them to cache peanuts in that tray, even though they do not desire peanuts at present (see Figure 3). As characterized, this argument rests on the assumption that an animal restricted to thinking only about how things are at present is thereby also restricted to acting only based on its present appetitive desires. Note that, in the case of food-caching birds in particular, there is no reason for making such an assumption. As Cheke and Clayton (2012) note, there is separate evidence that the motivational systems for eating and caching operate semi-independently from one another. Furthermore, they also describe a separate experiment, consisting only of the equivalent of the test trial in the study described above, which shows that, while specific satiety reduces the motivation to cache the pre-fed food type, it does not eliminate it.

Thus, insofar as Cheke and Clayton's (2012) study can be described as one in which the birds "overcome" a current desire in favor of one that will serve their future needs, the issue at stake cannot be that the motivation to cache the pre-fed food clashes with a current lack of motivation to eat that food, brought about by specific satiety. Rather, the only sense in which the birds can be said to "overcome" an existing motivation is that, by default, if pre-fed one food type, they have a motivation to cache less of that food type, and this changes into a motivation to selectively cache the pre-fed food type in a particular tray once they learn that that food type is desirable at retrieval from the relevant tray (see also Cheke & Clayton 2012, p. 174). This is entirely compatible with an account on which the relevant retrieval trials simply cause the bird to update its representation of which tray is a good location for caching which food.

2.3. Past and future thinking and animals: Concluding remarks

Comparison across Figures 1–3 should make one aspect of our account clear. In each instance, the representation that we are assuming underpins the birds' behavior, must necessarily *also* be part of what is represented according to an MTT account (i.e., that Tray 1 does not contain edible worms, that the stone should be chosen because it operates the apparatus, that Tray 1 is a good place to cache peanuts). Because of this, the representations we are positing cannot be considered to be implausibly ad hoc. Other questions one might raise with respect to our account also arise in the same way for accounts that postulate MTT abilities in animals. Thus, we have already noted that an MTT based interpretation of Clayton and Dickinson's (1998) study also has to assume the existence of some sort of mechanism that keeps track of time, which underpins animals' putative ability to remember "when" information. Similarly, in connection with our interpretation of Kabadayi and Osvath's (2017) study, questions might be asked about the conditions under which animals continue to represent an object as part of their current environment, even if it is outside their sensory range, and the conditions under which they stop doing so. Identifying these conditions is an empirical matter, and it is highly likely that the conditions vary by context and across species. But note that an explanation of the birds' behavior that ascribes to them an ability to imagine future events raises exactly parallel questions as to the conditions under which the animal does or does not assume the future event will occur.

The key point that the plausibility of our account hinges on is whether we are correct about the general means by which the birds arrive at the representations that underpin their behavior, that is, purely as a result of the operation of the temporal updating system. And, as should be clear, there are real constraints on what is available to such a system: Only a model concerning the world as it is at present is maintained, tensed content is absent from that model, and the correct functioning of the system depends on information about changes in the environment being received in the same order in which those changes happen. These constraints mean that, in explaining animal behavior, our account only allows for a distinctively narrow set of options. The alternative MTT account assumes that the birds arrive at these (very same) representations necessary to guide behavior as a result of first remembering a past or imagining a future event. Note, though, (and this is not always made clear) that MTT alone does not deliver these representations: that is, to guide behavior, remembering the event of caching worms has to be combined with other information about how long it takes worms to degrade and how much time has actually elapsed, and then an inference has to be reached about the contents of Tray 1. Thus, the plausibility of that account hinges not only on whether animals can be thought to engage in MTT, but on whether they can be thought to use the information it delivers alongside any other information that is required to yield a conclusion as to what needs to be done right now.

Before leaving the issue of animal cognition, we want to briefly consider two recent theoretical accounts that have also attempted to provide an alternative explanation of animals' performance in these sorts of tasks. Redshaw (2014) has argued that animals may have "uncontextualized" representations of events, by which he means representations that fail to locate these events in any specific temporal context (in his view, such contextualizing would require metarepresentational abilities). And in articulating his own dual systems theory, Keven (2016) has argued that animals (and young children) do not possess episodic memory but may possess event memories that are "perceptually-based [and] snapshot-like." Unlike episodic memories, he believes these event memories are not organized into narratives with temporal-causal structure. Both accounts therefore share the idea that animals have some type of free-floating representations of past (or future) events. Furthermore, although the two authors do not make this explicit in their discussions, their accounts are both compatible with one idea we are pressing, namely that there is no reason to believe that animals are capable of thinking about particular, unique, times. Nevertheless, the account we have put forward differs fundamentally from their accounts. The temporal updating system simply maintains a model of the world that records information about the environment and is updated in response to new information. Situations that obtained or will obtain at other times do not feature in such a model, even in an uncontextualized way. One way to put this is to say that on Redshaw's (2014) and Keven's (2016) accounts, animals are not truly cognitively stuck in time: they can mentally meander through time even if they have no idea where in time their meandering takes them. By contrast, on our account, animals really are cognitively stuck in time: they cannot think about other times at all.

Yet, while our account is thus more radical than those offered by Redshaw (2014) and Keven (2016), it can actually be seen to construe animals' behavior as more purposive than their accounts do. Note that, precisely because of their supposedly uncontextualized nature, it is ultimately not clear how exactly event memories of the type envisaged by Redshaw and Keven are supposed to explain the types of animal behaviors we have described – a point Redshaw himself seems to acknowledge in the context of discussing tool-saving behaviors in animals, which he characterizes simply as cases in which an uncontextualized representation of using the tool in question induces a bias to select it again. That is, it is not clear how uncontextualized representations of how things were or will be at unspecified other times can systematically and appropriately guide present action (e.g., how can they generate the types of representations described at the beginning of this section, such as "Tray 1 does not contain edible worms"?). By contrast, even though on our account animals are not capable of representing situations obtaining at other times at all, the model of the current world they operate with can clearly give them good reasons to act in certain ways. For instance, we assumed that the ravens in Kabadayi and Osvath's (2017) study choose the functional tool because it allows them to open the apparatus containing the food reward, which they represent as an item existing in their environment.

3. When do children acquire temporal reasoning abilities?

We have argued that there are good reasons to doubt whether animals can think about the past or the future, and therefore that they have anything more than the temporal updating system. We believe that the same is true of infants, although unsurprisingly, because of their limited motor skills, the paradigms used to look at memory (e.g., Barr et al. 1996; Rovee-Collier 1999) and future planning (e.g., McCarty et al. 1999) in infants are typically quite different from those described above that have been used with animals (though see Atance et al. 2015; Martin-Ordas et al. 2017; Russell et al. 2010; Russell et al. 2011). The challenge that our distinction provides for developmental psychologists is a more substantial one, though, than simply making the case that infants are capable only of temporal updating: it is to characterize the subsequent developmental emergence of the temporal reasoning system. In this section, we highlight some of the limitations in young children's temporal cognition and also some of the key developmental achievements that are required for mature temporal thought, focusing on two related areas: (i) the shift from relying on temporal updating to being able to reason about temporal order and (ii) the emergence of thought about other times. To anticipate, although we believe that infants operate only with the temporal updating system, and that temporal reasoning does not emerge until around 4–5 years, we think 2- to 3-year-olds may be at an intermediate developmental stage in which they are beginning to represent non-present situations and discriminate between them in a way that correlates with the difference between past and future situations. However, this is not genuine temporal reasoning, and children of this age may fall back on the temporal updating system.

3.1. Temporal updating versus reasoning about temporal order

Even infants can be sensitive to and learn about event order. Numerous studies of deferred imitation in infants have conclusively established that, at least by the second year of life, they can observe a short sequence of actions and reproduce those actions in the correct order even after a delay (e.g., Bauer & Mandler 1989; Bauer et al. 2000). Preschool children also rapidly acquire a repertoire of what have been described as "scripts" for routines (Nelson 1996).

These studies of infants and pre-schoolers suggest that children are very good at remembering and reproducing actions in the correct order. This basic ability in itself, however, is something that can fall within the scope of the temporal updating system rather than the temporal reasoning system. A key limitation of the temporal updating system that might be used to show whether children do indeed rely on it in learning about sequences is that the correct functioning of the system depends on it receiving information about events in the same order in which those events occur. We have described this as a signature limit of temporal updating, which contrasts sharply with a much more sophisticated way in which adult humans can deal with change over time, by engaging in genuine temporal reasoning about what happens when.

Although relatively few studies have examined temporal reasoning skills in young children, the evidence suggests that they struggle in situations in which the order in which they find out about successive changes may not reflect the order in which they happen – that is, in situations in which they cannot rely purely on temporal updating. In one study carried out by McCormack and Hoerl (2005), children learned that pressing (e.g.) a red button caused a marble to be released into a window of a box, and that pressing a blue button caused a toy car to be released. There was only ever one object in the window of the box at a time, so if the red button was pressed to yield a marble, on pressing the blue button the marble dropped away and was replaced by a car. Children also learned about two dolls that always acted in a particular order. The window of the box was then covered over, and two types of tasks were carried out. In one version of the task, children watched as one doll pressed the red button and then the other doll pressed the blue button. Under this condition, when asked which object was in the window of the box, even 3-year-olds were able to answer correctly. This task can be solved by temporal updating: children can sequentially update their model of what is in the box window: initially representing it as empty, then as containing a marble, and then as containing a car. However, in another version of the task, the dolls pressed their buttons behind a screen, out of sight of the children, and the dolls were then left beside the buttons they had pressed. Temporal updating could not be used to pass this version of the task, which required that the children infer the window's contents by reasoning about the order in which the dolls had pressed their buttons, and even 4-year-olds struggled to do this (see also McCormack & Hoerl 2007). Similar results were found in an earlier study by Povinelli et al. (1999), which used video clips to decouple the order in which children found out about two events from the order in which they actually happened.

Other studies have indicated that children of this age also have difficulties appropriately reasoning about temporal order relations in planning tasks, such as in circumstances where they have to think ahead about the order in which events are going to unfold in the future (Lohse et al. 2015; McColgan & McCormack 2008; relatedly see also Kaller et al. 2008; Tecwyn et al. 2014). Martin-Ordas (2018) asked children to select one of three objects to bring back to two rooms they had visited earlier. The correct answer was to choose the key needed to open a marble box containing marbles to use on a marble run. Although 3- and 4-year-olds correctly selected the key, they were unable to judge which room they should then visit first – the room with the marble box or the marble run room. It was not until children were 5 that they could reason appropriately about the order in which these future visits needed to happen.

The claim that children below 5 years find it difficult to reason about before-and-after relations in time might sound surprising given that children actually acquire the verbal terms "before" and "after" at an earlier age (Busby-Grant & Suddendorf 2011). There is, however, evidence regarding children's competence in using and interpreting those terms that is in line with what our account would predict. Specifically, they have difficulty correctly interpreting these terms when the order in which events are mentioned in a sentence does not match their order in the world (e.g., "Anna took off her coat after she took off her hat." Blything & Cain 2016; Blything et al. 2015), suggesting they use an order-of-mention strategy to interpret them. While there are a variety of interpretations of this finding (Blything et al. 2015; Pyykkönen & Järvikivi 2012), one possibility is that this reflects pre-schoolers' difficulties with temporal reasoning and their tendency to use the temporal updating system.

Taken together, the findings we have discussed here suggest that while even infants can learn about and be sensitive to event order, difficulties in reasoning about temporal order persist into the preschool years, with the findings from some studies suggesting that the errors children make may be due to falling back on the temporal updating system. By the time children are 5, existing evidence suggests that they have consolidated some important new temporal reasoning skills.

3.2. Thinking about other times

As with animals, there is considerable debate over how infants' and preschoolers' memory abilities should be characterized (e.g., Bauer 2007; Fivush 2011; Howe & Courage 1997). There have been attempts with various degrees of success to use a supposed "what-when-where" paradigm analogous to that used with animals (Burns et al. 2015; Martin-Ordas et al. 2017; Russell et al. 2011). Notably, even relatively older children struggle with tasks analogous to that of Clayton and Dickinson (1998) that require sensitivity to how long ago an item was hidden, which by our account of animal performance in such tasks is unsurprising because children would have no need in everyday life to have their search behavior governed by sensitive interval timing mechanisms. Performance in the tasks more typically used to measure infant memory (Bauer et al. 2000; Rovee-Collier 1999) can be straightforwardly accounted for in terms of the temporal updating system. However, it is less straightforward to explain preschoolers' verbal descriptions of non-current events merely in terms of the idea of temporal updating. Existing studies suggest that children who are 2–3 years old can talk about both past and future events, albeit often providing limited and fragmented information (Hayne et al. 2011; Peterson 2002; Weist & Zevenbergen 2008). It is widely accepted that children of this age can refer to things that are outside their current sensory scope (Sachs 1983), which is something that the temporal updating system could handle if these things are still part of their model of the world as it is now. However, children do not just refer to things outside their current sensory scope, they often use tense to describe non-current events, and we have assumed that the temporal updating system does not operate with tensed representations. Given that 2-3-year-olds can refer to events in the distant past and in the future, and 3-year-olds also use temporal adverbs (Weist & Buczowska 1987; Weist & Zevenbergen 2008), it might seem paradoxical to argue that they cannot think about the past or future.

We accept that children of this age do not rely only on the basic temporal updating system. However, we want to argue that they are at an intermediate stage at which they nevertheless do not yet possess genuine temporal reasoning abilities, and, in that sense, do not have proper concepts of the past or future. To make this argument it is necessary to consider more carefully the nature of the domain over which the temporal reasoning system operates. Temporal reasoning operates over the domain of times, with times arranged in a linear array such that each time occupies a unique unrepeated location in the array. Reasoning about such a domain involves a grasp of two distinctive types of systematicity that obtain within it. First, systematic before-and-after relations exist between points in that array because of its linearity – that is, for a sequence of times A, B, and C, if A happens before B and B happens before C, A must also happen before C. Second, which times are in the past, present, and future changes systematically with the progression of time: for the sequence of times just mentioned, if A is now present, then both B and C are in the future. But when B will be present, A will be past and C future, and when C will be present, both A and B will be past.

There is no reason to believe that young pre-schoolers can reason about the domain of time in this way. While they may talk about events that are in the past or the future, there is no reason to believe that they have a sense of where in the past or future those events are located, or a grasp of the systematic temporal relations that obtain between these events. In Tillman et al.'s (2017) recent study, 3-year-olds were unable to make judgments about the relative order of a set of past and future events (their previous and next birthdays, breakfast this morning, and dinner this evening). Indeed, 3-year-olds in this study were unable to reliably judge the deictic status of these events (nor the deictic meaning of time words such as "yesterday"). Similarly, Busby-Grant and Suddendorf (2009) found that children of this age could not discriminate the relative distances in the future of even very widely separated events (e.g., going home from day care versus next Christmas).

Important improvements in children's ability to think about the temporal locations of events occur between 3 and 5 years. There is evidence that by the time children are 4, they can begin to make some discriminations about the relative recency of unrelated events in the past (Friedman 1991; Friedman et al. 1995; Friedman & Kemp 1998; McCormack & Hanley 2011; though see Pathman et al. 2013). However, even 4-year-olds struggle to order the times of events in the future (Friedman 2000; McCormack & Hanley 2011), or to judge the remoteness of past and future events (Busby-Grant & Suddendorf 2009; Tillman et al. 2017). Moreover, a number of studies have shown that they tend to confuse near past and near future times (Friedman 2003; Friedman & Kemp 1998). Indeed, the ability to order events in time continues to improve substantially over the next few years (Hudson & Mayhew 2011; Pathman et al. 2013; Tillman et al. 2017).

We have suggested that reasoning over the domain of times involves not just understanding the relations that obtain between points in time but also understanding that which points in time are in the past, present, or future changes systematically with the progression of time. Extremely few studies have addressed children's ability to engage in the kind of temporal perspective taking that grasping this requires, but those that have indicate that children below 4 do not have this ability (Cromer 1971; Harner 1980; 1982). In Cromer's task, children had to consider the deictic status of an event from a point in time that was not the present. For example, children were told a story about a girl who visited a farm where a number of things happened, including her seeing birds, and who then returned from the farm. Children had to judge (e.g.) at what stage in the story the girl could refer to seeing the birds in the past tense. It was not until children were 4–5 years old that they were able to answer these types of questions correctly.

Coupled with the findings discussed in the last subsection, the evidence weighs heavily in favor of the idea of an important transition in the period from 3-5 years in children's ability to engage in temporal reasoning. During this period, children acquire mature concepts of time and start to be able to reason about the domain of linearly ordered times. This leaves the question, though, of how we want to characterize temporal cognition in the early preschool years, if we want to argue that children of this age cannot properly think about the past and future. We suggest that at this age children are able to make some sort of discrimination between situations that have obtained and situations that are yet to come. One way to put this is to say that they may retain models of the world that have been superseded (i.e., of past states of affairs), or models of the world as it has yet to be (i.e., of future states of affairs). As demonstrated by generally accurate use of past and future tense, they can usually appropriately discriminate between these models, in a way that corresponds to which of these two types they belong to. Nevertheless, we do not believe that children of this age are treating some models as descriptions of situations located at specific past times and others as descriptions of situations located at specific future times. Rather, we believe that children of this age may simply make a categorical distinction that marks a difference between these two types of situations; specifically, we believe that children discriminate between situations that are no longer alterable and situations that are still potentially alterable (see McCormack 2015; McCormack & Hoerl 2017, for considerably more detail on this proposal and our developmental model). However, this is different from having one unified model of the world within which time itself is represented. Having such a unified model goes beyond just representing certain sets of states of affairs and being able to discriminate between them. It involves representing time as one of the dimensions along which reality is extended, and as a linear dimension along which these sets of states of affairs can therefore be organized, so that they can all be captured in one set of systematic temporal relations in which they stand to each other. Temporal reasoning, in other words, operates with a four-dimensional picture of reality, on which everything that happens can be described by giving its location and the time at which it happens. It is the discovery of time as this fourth dimension that is the crucial step in the transition to a temporal reasoning system.

Space precludes us from commenting more than very briefly here on further developmental questions regarding cognitive prerequisites for the development of temporal reasoning – in particular regarding claims that have been made to the effect that temporal reasoning requires language (Bennett 1964), or that it requires a capacity for metarepresentation (Redshaw 2014). With regard to the role of language, we believe it is plausible (although we will not develop the argument here) that acquisition of the basic temporal concepts discussed here requires language, perhaps because it is only through discussing non-current events with others that children begin to grasp how such events are temporally organized (Hoerl & McCormack 2005; Welch-Ross 2001). This does not mean, though, that children learning different languages or growing up in different cultures acquire different concepts of time. We assume that our description of the temporal reasoning system captures basic and universal features of human thinking about time, and this includes a notion of time as linear. Although cultures may differ in the extent to which they emphasize cyclical or repeating patterns in time, we follow Gell (1992) in assuming that linearity is a universally basic feature (McCormack 2015, McCormack & Hoerl 2017). The features of the temporal reasoning system that we have highlighted will of course be overlaid by further culturally specific constructs, such as different ways of metaphorically mapping time onto space or of measuring time using a calendar system. These culturally specific aspects of development have a protracted developmental time course (Friedman 2003; McCormack 2015).

With regard to the issue of metarepresentation, we note an interesting structural parallel between the account we have proposed of the development of temporal reasoning capacities and Perner's (1991) influential account of the development of metarepresentation. On Perner's account, children move from having only one model of the world through an intermediate phase of being able to switch between different models, before finally being able to conceive of them as different representations of the same reality. On our account of the emergence of temporal reasoning, children are initially capable only of temporal updating, and thus operate with a tenseless model of the world. They then begin to be able to maintain models describing non-current states of the world but they do not represent these as states organized along a single temporal dimension, and therefore do not grasp the systematic temporal relations between them. In acquiring genuine temporal reasoning, a unified model emerges that allows children to represent how these states are temporally organized and interrelated.

Although the structural parallel is interesting, we note, however, that there is an important difference between Perner's (1991) description of the emergence of metarepresentation and our description of the emergence of temporal reasoning, in that the accounts differ in terms of the type of systematic relations between models that children need to learn to grasp. Perner's claim is that children need to grasp how different models of the world are related to the actual world – specifically, that they are representations of reality – and it is through this that children understand how the models relate to each other, as different possible ways of representing the very same world. That is, grasping the type of systematic relations that Perner is interested in is a consequence of understanding the representational nature of mental states. In our account, children must grasp the systematic temporal relations between different models of non-current states of the world by realizing they are located at points on the same timeline. It cannot be straightforwardly assumed that grasping this type of relation necessarily requires grasping the representational nature of mental states, although we recognize that there is a more detailed developmental story to be told about how this new ability comes about, further discussion of which we provide elsewhere (Hoerl & McCormack 2005; McCormack 2015; McCormack & Hoerl 1999; 2001; 2017).

3.3. Animal cognition revisited: Lessons from developmental studies?

Before turning to adult human cognition, we want to briefly consider whether the findings of developmental studies might help illuminate what types of animal research would be capable of providing a test of the hypothesis that animals rely only on the temporal updating system. Developmental studies have looked in detail at children's ability to represent and reason about event order information, and two types of findings are of note. First, developmentalists have devised studies that provide children with information about changes that have happened in a sequence, but do not provide this information in the order in which the changes themselves unfolded (both by showing misordered videoclips that children need to mentally re-order [Povinelli et al. 1999] and by requiring children to infer the sequence from two pieces of information that are presented simultaneously [McCormack & Hoerl 2005; 2007]). The temporal updating system as we have described it can only provide an accurate model of how the world is now if changes are encountered in the sequence in which they actually occur, so reliance on that system would result in task failure. Second, we also note that some developmental planning tasks require that children do more than simply select a tool that is functional for obtaining a reward that exists somewhere in their current environment. In McColgan and McCormack's (2008) study, children must bear in mind the order in which events are going to unfold in the future and appropriately place an object so that it will be encountered later at the right point in a sequence of future events; in the study of Martin-Ordas (2018), children must think ahead about the order in which they need to visit two rooms so that they are appropriately prepared when they later encounter the reward apparatus. We anticipate that it might be possible to devise animal versions of both these types of studies, and such studies would prove particularly illuminating in testing our hypothesis about limitations in animal cognition.

4. Dual systems in adult human temporal cognition

Once the capacity for temporal reasoning has developed, does the temporal reasoning system simply replace the more primitive temporal updating system, or does the temporal updating system remain in operation even in adults? In this section, we consider some evidence – albeit from a somewhat unusual source – suggesting that even adults still operate with the temporal updating system alongside engaging in temporal reasoning.

A claim familiar from some of the existing literature on dual systems perspectives on cognition is that one of the hallmarks of two systems being at work alongside each other in people's thinking about a particular domain is that they can give rise to cases of what Sloman (1996, p. 11) calls "simultaneous contradictory beliefs" about aspects of that domain, where "belief" is to be understood as "a propensity, a feeling or conviction that a response is appropriate even if it is not strong enough to be acted on" (Sloman 1996, p. 11). The idea is that in a case in which the two systems yield diverging outputs, the more primitive, automatic, system still delivers its verdict, even if it is not endorsed by the more deliberate reasoning system, giving rise to a felt pull toward making one judgment, despite this judgment being rejected as incorrect.

We believe that a careful consideration of aspects of what might be called adults' "naïve theory of time" provides evidence for the existence of such simultaneous contradictory beliefs also in the domain of temporal cognition. Unlike naïve theories of some other domains (Gelman 2006), the nature of this naïve theory of time still awaits systematic empirical attention, although there is growing interest in this topic among philosophers (see, e.g., Braddon-Mitchell & Miller 2017; Callender 2017). Their interest stems from their belief that there are particular elements of people's naïve theory of time that cannot simply be explained in terms of the physics of time, that is, as reflecting features of time as it figures in physical theory. This raises the question as to how exactly these elements of people's naïve theory of time should be characterized and what their actual psychological sources are. Using the term "manifest time" to refer to humans' naïve theory of time, Callender (2017, pp. 23f.) puts the point as follows: "[Once] one removes the project of explaining manifest time [in terms of physical reality, one] places it on the desks of psychologists. The psychologists, however, don't know it's on their desk. The end result is that manifest time remains unexplained."

One core ingredient of humans' naïve theory of time that has been argued to require such a psychological explanation is the belief that there is an objective flow or passage of time for which there is no spatial equivalent. This belief appears to be universal (Gell 1992), despite cultural variations in a number of other aspects in which time is conceptualized (Boroditsky 2011). It has also been documented in the context of research in psycholinguistics on limitations on the extent to which aspects of time can be captured by spatial metaphors. There, it has been argued that, while spatial metaphors for time are ubiquitous, there is also a set of metaphors for time that take change or motion as their source, pointing to a unique attribute of "transience" involved in the concept of time, which cannot be captured other than in terms of notions that themselves invoke time (Galton 2011).

What exactly is involved in thinking of time as flowing or passing? Philosophers have offered an analysis of this ingredient of people's naïve theory of time, according to which it involves the combination of two components: the belief that there is just one objectively present moment in time, and the belief that which moment in time is objectively present changes over time (Leininger 2015). The claim that people's naïve theory of time involves the belief that there is one *objectively* present moment in time is best illustrated by contrasting what people take to determine "now" with what they take to determine "here." What counts as "here" is clearly just a matter of where the speaker using that word is located, and thus a place is "here" only for the speaker who is using the word. A particular place's being "here" is not a property of space itself; it is purely a matter of perspective. By contrast, people's naïve theory of time does not conceive of a particular time being "now" as similarly being purely a matter of perspective. Rather, which moment in time is present is taken to be a property of time itself (and hence the same for everyone), and moreover a property of time that itself changes over time. It is in this sense that the naïve theory of time involves the belief that there is one objectively present moment in time. Moreover, there is a crucial connection between the belief that there is one objectively present moment of time – one objective "now" – and the belief that there is such a thing as the passage or flow of time. The idea of the flow or passage of time requires that there is an objective "now" because it assumes that there is something about *time itself* that changes over time – that is, there is a property that time itself has that is different from one moment to another, namely which moment of time is present. Time is assumed to be fundamentally unlike space in this respect, because space does not possess such a property – where "here" is does not change because space itself changes, but only because the location of the speaker using the word changes. By contrast, the idea that time flows or passes assumes that which moment in time is "now" is an objective matter, a property possessed by time itself. By the same token, though, it also requires that which moment in time is thus objectively present is something that does change over time. As time goes on, the objective now occupies successively later points in time. It is this change that time itself is assumed to undergo over time that the passage or flow of time consists in.

As we mentioned, much recent debate in the philosophy of time has focused on whether components of the naïve theory of time such as the idea that time passes or flows reflect how time really is, particularly in the light of contemporary physics. We are not directly concerned with this debate here (see Rovelli 2018 for an accessible discussion). Rather, we want to consider the idea of the passage or flow of time in the light of our dual systems theory of temporal cognition. In what follows, we wish to defend two claims: (i) There is an inherent contradiction in people's naïve theory of time, insofar as it contains within it both the belief that there is an objective present and the belief that which moment in time is objectively present changes. (ii) This contradiction in people's naïve theory of time can be explained in terms of the co-existence of the dual systems we have identified.

Arguments to the effect that the naïve view of time is inherently contradictory in virtue of containing within it the idea of the passage or flow of time are in fact long-standing within philosophy (Bardon 2013; McTaggart 1908). Price (2011) has argued that the basic problem with any picture of time involving that idea is that it wants to be *exclusive* and *inclusive* at the same time. The picture is exclusive insofar as one moment in time is supposed to enjoy some form of objective privilege in virtue of being the one moment in time that is present. Yet, it is also supposed to be part of the picture that which moment in time is present changes, meaning that more than one moment in time gets to be present. This implies inclusivity rather than exclusivity: because each moment in time gets to be present when its time comes, no one moment can be objectively privileged. That is, each moment in time is on a par with all others in being the present moment in time when it is that moment in time. One might try to respond to this by holding on to the claim that the present moment is special, but also claim that which moment is present depends on what time it is. The difficulty with responding in this way is that it makes which moment in time is present dependent on what time it is considered from, rather than it being an objective property of time which moment is present. This difficulty becomes clear if one returns to the case of space. One could say in a similar way that the place indicated by "here" is special in some sense, that is, because it is the place that the person referring to "here" is located in. Clearly, different places then get to be special in that sense as the speaker moves around (and other places get to be special for other people). But this means that their specialness does not stem from something objective about the spatial locations themselves, their specialness is simply a matter of perspective. Thus, accepting that which moment in time is present is similarly just a matter of perspective requires giving up on the idea of an "objective now" and with it the idea of the passage or flow of time.

In as far as the naïve theory of time, and more specifically the idea that time passes or flows, does indeed involve a set of simultaneous contradictory beliefs along these lines, how might the dual systems account of temporal cognition we have outlined account for how they arise? The picture of time that Price describes as "inclusive" is one on which all times are indeed on a par with one another and events and states of affairs are thought of in a way that is temporally qualified: they are thought of as taking place or obtaining at certain times, with other events or states of affairs taking place or obtaining at other times in exactly the same manner. This is, broadly speaking, the kind of way of thinking about time people employ when using the temporal reasoning system, in which time is thought of as a linear dimension along which reality is extended. Some of the key manifestations of this type of thinking are the ability to use a clock-and-calendar system and the ability to engage in MTT. Using the temporal reasoning system can enable people to recognize that the present does not really have an objectively special status, and that thinking of certain events as present is actually simply a matter of locating them with respect to one out of many possible perspectives on time, just as thinking of a place as "here" is a matter of locating it with respect to one out of many possible perspectives on space.

Insofar as the idea of there being one objectively privileged present moment in time nevertheless also figures in everyday thinking about time, we want to suggest, its source is a residual tendency that people still have to think of the world using the other, less sophisticated temporal updating system (for related ideas, see Falk 2003; Prosser 2006). How exactly might the existence of the temporal updating system explain the sense in which it seems to people that the present somehow has a privileged status? When the latter idea is discussed in the literature on the metaphysics of time, it is sometimes further specified as the idea that people have an impression that present things exist *simpliciter*, without temporal qualification (Skow 2011; Zimmerman 2005). That is to say, it is not that people's impression is that past and future things do exist, just not right now in the present. Rather, the impression is that past and future things simply do not exist at all – only present things do. As we have seen, representing present things in a way that is not temporally qualified is also a feature of the model of the world maintained by the temporal updating system. It is a model of the world that concerns the world only as it is at present. When that model is updated in response to a change in input, it is simply replaced by a new model, with nothing in the new model representing that things were previously different from how they are now. But this implies that each model fails to identify the then-current situation as only one among many, temporally speaking. Nothing within the system signals that its representations represent just how things are at one time, with there also being other times at which things are different. In this way, the operation of the temporal updating system might explain a bias people have toward thinking that there is only one objectively present moment in time and that only what is present exists or is real. People seem to have this bias even though they can also recognize, using the temporal reasoning system, that what they think of as the present is only one perspective in time among many others. In this way, the operation of the dual systems gives rise to contradictory elements in people's naïve theory of time.

Note that the issue here is not just one of diagnosing a contradiction implicit in people's everyday thinking about time and providing an explanation for it. Unlike most other contradictions, in this case, the contradiction is not simply eliminated once people notice it. Philosophers who have come to the firm conviction that time does not really pass or flow, or even that the idea of time as passing or flowing is incoherent, frequently admit that they nevertheless still have this impression of time (for one example, see Ismael 2017, p. 35). Similarly, even Einstein, who saw clearly that his physics ruled out any "objective now" continued to be troubled by what he called the "problem of the Now" (Carnap 1963, p. 37). It is the phenomenon of "simultaneous contradictory beliefs" in this more specific sense that dual system accounts have been claimed to be able to be particularly well suited to explain (Sloman 1996).

5. The two systems and intertemporal choice

We now turn to one final area of research that we think our dual systems account of temporal cognition can bear on in interesting ways, which is research on intertemporal choice (i.e., choices that involve assessing the relative value of rewards available at different time points). The idea that some form of dual systems view might usefully be brought to bear in explaining some of the phenomena surrounding intertemporal choice can already be found in the existing literature. Perhaps the most influential two-system approach to intertemporal choice is Metcalfe and Mischel's (1999) hot/cool systems analysis of delayed gratification. However, their distinction is one between an emotional system and a cognitive system, whereas we have drawn a distinction between two different cognitive systems: one for temporal updating and one for temporal reasoning. Our aim is therefore not to replace their distinction or similar existing dual process approaches to delayed gratification. Rather, the idea of two different cognitive systems that deal with how things unfold over time might provide us with a more fleshed-out picture of how exactly the processes already appealed to in the existing literature might be involved in delayed gratification. In this section, we want to argue that the two different systems provide for two quite different types of mechanisms that might facilitate delay of gratification. Note that our aim is simply to describe these two possible mechanisms for delaying gratification, and how they relate to the distinction between the temporal updating system and the temporal reasoning system; we do not attempt to explain the broad set of phenomena that have been extensively studied under the heading of intertemporal choice (e.g., the shape of the temporal discounting curve).

The first, more basic form of delayed gratification might be illustrated by considering a proposal Boyer (2008) has put forward concerning what he sees as the function of future episodic thinking. Boyer thinks that simulation of future outcomes "can act as a calibration device by triggering emotional rewards that accurately reflect the emotional impact of [these outcomes] and are immediate and, therefore, bypass the usual discounting of future consequences of actions" (Boyer 2008, p. 221). That is, mentally "pre-experiencing" the reward allows people to give it due weight in their decision making and avoid discounting. Boyer advertises this as a way in which future episodic thinking can aid in delaying gratification. Interestingly, though, its net effect could actually also be described as that of diminishing the relevance of time by allowing the chooser to "pre-experience" the reward. While it is true that the mechanism is triggered through a representation of the future reward, and in this sense involves temporal reasoning, we want to suggest that the subsequent effect of simulating that reward is actually to bring it within the purview of the model of the world maintained by the temporal updating system. The reward can then figure within that model as a more valued alternative to the immediately obtainable award, motivating the chooser to take steps to obtain it instead. To flesh out this idea further, we can draw on some features of the temporal updating system that we have already noted.

As we explained, the model of the environment maintained by the temporal updating system is best understood as a model in which time simply does not figure. There is therefore no way for a future reward to figure in that model as such, that is, as one that exists, but at a time different from the present. However, things can figure in the model of the world maintained by the temporal updating system even if they are not immediately accessible. For instance, the model may represent a reward as existing in the environment, even though it may not be obtainable immediately because it is not within current sensory scope. We hypothesize that simulating a future reward, in the way envisaged by Boyer, allows the chooser to represent the (de facto) delayed reward in its model of the world in this way: both the delayed and the immediate reward are represented as potential objects for present choice, thus overcoming the discounting of the future that normally comes with using the temporal updating system. Note, though, that we are not arguing that this way of overcoming discounting requires only the temporal updating system. The temporal reasoning system is required because it triggers the project of simulating the future reward; the updating system itself does not represent future states of affairs. However, once the future reward is simulated, it can then feature in the model of the world used by the temporal updating system as an available choice.

We want to distinguish this first way of mitigating temporal discounting, which primarily exploits cognitive resources available within the temporal updating system, from a second, more sophisticated one, in which temporal reasoning plays a much more central role. Put briefly, the key distinction might be put as follows: The kind of mechanism just described involves the chooser representing two choice objects – an immediately available smaller reward and a not immediately available larger reward – and putting themselves in a position to be able to weigh them against each other by bringing both of them within the purview of the model of the world maintained by the temporal updating system. In delayed gratification involving temporal reasoning, by contrast, it is not just such individual choice objects that are weighed against each other; rather, what becomes a matter of choice is how the chooser wants events in their future to unfold over time. Specifically, they need to decide how they want rewards to be distributed over the timeline that they represent as stretching into the future, and in this sense they are reasoning about time itself. As we might also put it, whereas the mechanism we have previously described allows the agent to give the future reward due weight through setting aside its futurity, temporal reasoning can mitigate discounting by allowing the agent to give the future itself due weight in their deliberations.

In the preceding section, we described the picture of time that the temporal reasoning system operates with as an inclusive picture of time, following Price (2011), on which different times are seen as being on a par with one another, rather than one time – the present – having a special status. This feature of temporal reasoning, we want to suggest, is what allows agents to switch from simply trading individual rewards off against each other to considering how they want rewards to be distributed over the timeline stretching into the future. There are a number of different factors that have already been shown to impact on intertemporal choice, which might be seen to affect it through facilitating reasoning about time in this way.

For example, using a number of different real-life measures such as saving for retirement, adopting a healthy lifestyle, and practicing safe sex, Chen (2013) has shown that speakers of languages that allow for future events to be spoken of in the same grammatical forms as present events show more future-oriented behavior than speakers of languages that require a grammatical future marker. It is unlikely that this is due to the former simply ignoring the difference between present and future events, or imagining future events as present and using a mechanism of the type described by Boyer to delay gratification. At least some of the prudential behaviors studied by Chen involve fairly complex long-term goals, imagining the attainment of which is unlikely to have a strong, immediate hedonic effect. Rather, we believe that what lies behind these findings is that languages with an obligatory future tense marker encourage a focus on the present, because they encourage thinking of future events as somehow having a different status than present ones. By contrast, languages that allow for thinking of future events in the same grammatical categories as present ones, facilitate thinking of future events as having the same status as present ones, despite being temporally distant, and therefore as ones that ought to bear a similar weight in one's deliberations. Other existing studies might be seen in a similar light. For instance, a number of studies that have followed up Boyer's (2008) suggestion that episodic future thinking plays a special role in supporting delay of gratification (e.g., Benoit et al. 2011; Lin & Epstein 2014; Peters & Büchel 2010) have demonstrated that simply getting people to imagine the future per se (i.e., not just imagining rewarding events) reduces temporal discounting. Even simple manipulations that vary the way relevant future points in time are characterized, such as presenting them as dates rather than delays, impact on degree of discounting (Read et al. 2005).

Crucially, the temporal reasoning system allows individuals to think of their lives as *temporally extended projects*. This requires more than just an ability to trade individual momentary outcomes off each other, but the ability to think of such outcomes as forming a pattern through time that is consistent with the way they want to shape their lives. The broad idea that people's current choices are influenced by how they want their lives to unfold over time has featured centrally in a number of different theoretical frameworks in social psychology (e.g., Markus & Nurius 1986; Oyserman & James 2011), and we will not defend this idea here. Rather, we want to emphasize the way of thinking about time that this involves, and the role that way of thinking of time therefore plays in intertemporal choice.

On this picture, in deciding what choice is the best fit with how one wants the temporally extended project of one's life to unfold, times are represented as unique, unrepeating points on a timeline of one's life, that is, as what we have termed above as "particular times." This becomes vivid if we consider that, in some circumstances, what makes intertemporal choices important is the lack of an opportunity to revisit them (e.g., deciding whether to spend now rather than save for one's pension, deciding whether to have children). When making intertemporal choices using the temporal reasoning system, choice points are considered as bifurcation points in linear time, with choices determining whether one's life unfolds one way or another. This can indeed sometimes result in the decision to delay gratification, but notably this second mechanism for mitigating temporal discounting is in an important way more flexible than the first one we described involving the temporal updating system. As pointed out by Bulley et al. (2016), depending on how the future is likely to unfold, it may sometimes be the right choice to take the smaller, sooner reward instead of waiting (perhaps in vain) for the larger, later one. Thus, while temporal reasoning can facilitate delayed gratification, it might also sometimes make it apparent that it is better to "seize the day."

In this section, we have distinguished between two mechanisms facilitating delay of gratification – one that relies on the temporal updating system by bringing the future reward into the current model of world, and one that relies on the temporal reasoning system by allowing people to think about their lives as timelines along which they decide to have a particular temporal profile of reward. This raises important questions about the circumstances in which these mechanisms might be put to use, and about how they are related to each other. With regard to facilitating delay of gratification, we do not view these mechanisms as typically being in conflict with each other. Indeed, we have stressed that the first mechanism draws on the temporal reasoning system to initiate a simulation of a future reward that can then fall under the purview of the temporal updating system. Which mechanism is effective in helping people delay gratification may depend on the nature of the choice. For example, it may be that it is particularly helpful to delay gratification of purely hedonic rewards by imagining those future rewards as actually present right now, whereas delay of gratification for rewards that are meaningful primarily in the larger context of one's life or individual identity might be best facilitated by thinking about one's life as a temporally extended project. There also may be group or individual differences; for example, amnesic patients who lack the ability to engage in detailed simulation of future events may base their intertemporal choices primarily on reasoning about the timeline of their future lives (this type of reasoning appears to be intact in such patients; Craver et al. 2014b).

6. Concluding remarks

We have argued that our dual systems approach helps to shed light on a variety of issues ranging from how to characterize animal cognition to the metaphysical assumptions that seem to be part of people's naïve theory of time.

We have sided with those who reject the idea that animals are capable of MTT, arguing that animals are not capable of thinking about the past or the future at all. Part of what motivates our arguments is the idea that it is at least not obvious how much use animals would have for the idea of particular past and future times different from the present (on this, see also Campbell 1996). What we have said in this article does imply that there are some benefits that come with being able to engage in temporal reasoning, for example when it comes to dealing with situations in which information about successive changes is received in a different order from the one in which they happened. However, we hypothesize that temporal reasoning abilities have not evolved in animals because opportunities to benefit from knowing that a situation of a particular kind obtained at a unique time in the past are relatively rare, because that time itself will never come around again. By contrast, there are obvious benefits in possessing a general learning system geared toward encoding and retaining information about regular, stable, or reoccurring features of the environment, because such information may be of use on numerous occasions when these features are encountered again.

As humans, we have developed the ability to make time itself an object of thought, to think of the world as extended in four dimensions, one of which is the temporal one. Given what we have just said, we think it is right that questions as to the primary adaptive function that this ability has evolved to serve in humans' lives have recently started to attract researchers' attention (see, e.g., Mahr & Csibra 2018). However, as we have tried to argue, there are also reasons for thinking that the more primitive temporal updating system that animals rely on in negotiating the world, in which time is not represented, is still active in humans too, alongside the capacity for temporal reasoning. This may be part of the explanation as to why time remains a phenomenon we can get deeply puzzled by.

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Open Peer Commentary

Are counterfactuals in and about time?

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Abstract

We discuss whether the two systems approach can advance understanding of children's developing counterfactual thinking. We argue that types of counterfactual thinking that are acquired early in development could be handled by the temporal updating system, whereas those that emerge in middle childhood require thinking about specific events in time.

One way in which thinking about time is particularly sophisticated is when we speculate about what might have been (counterfactual thinking, e.g., If I had left earlier, I would have caught the train). Two different accounts of the development of counterfactual thinking exist. Broadly, one account argues that counterfactuals are early developing and cognitively easy, whereas the other argues that they are late developing and cognitively challenging (see a recent exchange between Beck [2015a; 2015b] and Weisberg & Gopnik [2013; 2015]). Hoerl & McCormack (H&M) do not discuss counterfactual thinking in their article, but the topic is worth considering, because (1) their dual systems model provides insight into the debate on the emergence of counterfactual thinking, and (2) counterfactual thinking offers additional evidence to support their approach.

If one takes the broad approach to defining counterfactuals, including all worlds that are not currently true, then many types of counterfactual thinking, such as pretence and fiction, do not require a temporal reasoning system because they have an atemporal relation to reality. These are not imagined worlds in the past or future, but they exist in parallel with the real world. They may include events unfolding in time, such as an extended pretend tea party, which can be handled using temporal updating. More relevant for this commentary is the possibility that future hypotheticals (questions about how the world will be in the future), can also be handled by the temporal updating system if one allows for imagined updates to the current world model. For example, in one study, a car was driven from the midpoint on a road to one end. Even 3-year-olds easily answered, "What if next time he drives the other way, where will he be?" by pointing to the other end of the road (Robinson & Beck 2000; see also Beck et al. 2006). Although this appears to be speculation about a future world, it could be the output of an updated model of how the world is without any temporal reference. Reasoning with imagined extensions of actual events has been previously described as basic conditional reasoning (Perner & Rafetseder 2011).

Psychologists who take the narrow approach treat tasks that involve thinking about alternatives to *past events* as a special type of counterfactual and assume that these thoughts about "what might have been" involve thinking about events in time (which would require the temporal reasoning system). However, 3-year-olds perform remarkably well on some of these tasks. For example, in Buchsbaum et al. (2012), children learnt that one type of block, a zando, made a machine play music. Even 3-year-olds could answer the question, "If this one were not a zando, what would happen if we put it on top of the machine?" (right answer: no music). We wonder if the question does not require thinking back in time. Despite its broadly counterfactual nature one can reach the right answer by updating a current model of the world: "Taking it from now" how will the world be if I imagine the block not being a zando?

Two recent studies have used doubly determined events, where a single outcome has more than one potential cause, to try to ensure that children had to consider the specific events in the past. In McCormack et al. (2018), two birds travelled down two separate slides towards a pig. If they reached this pig, it would get knocked over, but sometimes their paths were blocked. Children were asked various counterfactual questions, such as, "If I had not rolled the red bird that time, would the pig have fallen down?" In a study with very similar causal structure, Nyhout and Ganea (2018) used a block-activated machine. A blue block was placed on the machine, activating it to light up, and then a green block was added (also causally effective). Children were asked, "If she had not put the green one on the box, would the light still have switched on?" Children did not give the right answer to McCormack et al.'s question until they were 6, whereas 4-year-olds gave correct answers to Nyhout and Ganea's question. Perhaps the two systems approach can help us understand this discrepancy in performance. In Nyhout and Ganea's task, the music box is presented on a video, which is stopped when children are asked the question. H&M's temporal updating system can include things outside their "current sensory scope" in the current world model. Perhaps the child's current model still includes both objects on the box so that he or she can answer the question by updating: If I remove the green block from my model, is the machine still on? A subtle difference in presentation meant that the event in the McCormack task is completed and in the past: The current model has birds at the bottom of their runs and the pig has fallen over. The child can't start from here to update her model; she needs to simulate a new version of events that are now in the past. This is beyond the temporal updating system. An important step to test this suggestion would be to contrast closely matched doubly determined scenarios where the outcome is ongoing (and can be updated) or completed (n.b. Riggs & Peterson [2000] contrasted counterfactuals about ongoing and completed events, but their scenarios were singly determined and may not have necessitated thinking about events in time).

Future work on the development of counterfactual thinking will benefit from considering the temporal aspects of the demands being made on the child. We are optimistic that drawing these distinctions between different types of counterfactual thinking will be useful in understanding why some counterfactuals, those that are in and about time, are particularly challenging for children and only emerge in middle childhood when the temporal reasoning system is in place.

Time, flow, and space

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Abstract

Does a temporal dual process theory explain the illusive flow of time? I point out one shortcoming of such a theory and propose an alternative that does not require either dual cognitive processes or demand such a stark asymmetry between space and time in the brain.

Time flows, but space does not. Languages the world over attribute to time a dynamic quality not also attributed to space. Relative to a deictic center, we chop up the world temporally into past, present, and future, and we chop up the world spatially into here, there, right, left, up, down, and so on. As we move about, both deictic structures update themselves. What was once there becomes here. What was once future becomes past. Crucially, this updating happens monotonically in one direction in the case of time. That is why time flows, but space does not. Although our construals of temporal flow may vary with language and culture, representing time with flowing temporal deictic structure seems very nearly universal.

What explains this? Some philosophers suspect a kind of contradiction lurks at the heart of time flow. McTaggart (1908) argued that combining temporal deictic structure (past, present, future) with temporal sequential structure (earlier, later) is inherently incoherent. More recently, Price (2011) writes that we want a theory of time that is at once both exclusive – privileges only present times – and inclusive – acknowledges that all times exist. Because a signature of a dual process theory is supposed to be the occurrence of simultaneously contradictory beliefs (Sloman 1996), Hoerl & McCormack see this as an opportunity to put their dual temporal systems theory to work. The impression that time flows, they say, is due to a clash between our primitive temporal updating system, which represents only the present, and our more sophisticated temporal reasoning system, which represents past, present, and future events.

What I like about this rich and original idea is that, if true, it would explain the near universality of the time flow phenomenon. If mature human beings have these two systems and time flow is a result of their conflict, we should expect claims about time flowing to be widespread. However, I do not think that this can be the full story about flow nor do I think this is necessarily the most parsimonious way to get this result.

What this account misses in our naive account of time flow is the idea that *something* flows. There is more to our talk and thought of flow than a tension between a wide existential quantifier (quantifying over all times) and a narrow one (quantifying only over present events). That conflict will generate tension, but it will not underwrite the beliefs that *future events draw nearer* and *past events recede*. I am closer to my birthday than I used to be. You too. The temporal monotonic updating is updating something. To make sense of the above beliefs, something must endure (or appear to endure) through time (Velleman 2006). The naive theory of time is not fundamentally accurate. Still, to explain flow, even if it is illusory, we must explain this feature of it.

Some have suggested that what flows is the self (Velleman & Callender 2017). The self may itself be illusory in some sense. Based on that theory, the self is constructed along one's world line, giving the appearance of something enduring when nothing in fact is. Whatever the right answer, the dual systems approach needs supplementation. It gives us friction, not flow.

The paradigmatic type of motivation for dual process theories is the occurrence of simultaneously contradictory beliefs. Evidence that we have such beliefs typically appeals to performance error (e.g., violating the probability calculus) and a residual tendency to still make the error even when we realize we are mistaken. The well-known conjunction fallacy illustrated by the Tversky and Kahneman (1983) case of Linda the bank teller is an example. It is the cognitive counterpart of a perceptual illusion. Learning about the mistake (if it is one) does not eliminate the perception in the illusion case or the thought in the belief case. But where is the performance error? Everything works smoothly. I never confuse tomorrow with today. So I wonder if positing dual systems is really called for on the basis of flow. Perhaps I'm simply thinking one thing and then another.

Here is an alternative suggestion that also explains Price's inclusive versus exclusive tension in terms of a clash: Temporal flow partly stems from a mismatch between perceptual and cognitive systems. The former gives us short temporally extended presents. The latter extends over more time. This perceptual/cognitive tension would make the flow of time more like the illusion it is commonly said to be. We are already committed to both systems. Unless a cognitive/cognitive clash is better for some reason than a perceptual/cognitive clash, then this mismatch may be a better explanation.

Finally, why does space not flow according to the authors? One can easily imagine a similar conflict in the spatial case between our representations of the spatially proximate and the spatially distant. The authors have a fine answer: In the temporal case, we have two systems, whereas in the spatial case, we have only one. Animals and young children presumably come (or are earlier) equipped with a single sophisticated spatial reasoning system, so there are not two conflicting systems generating flow. Note that the authors' answer must rely on the stark asymmetry that they posit between space and time in the brain.

I do not have space to develop the point, but against this, I want to advocate for conceiving of the brain as employing a generalized system that constructs a *spatiotemporal* representation of the world, not separate spatial and temporal systems like those assumed here (Arnold 2013). Such a system seems a better fit with the data. We live and evolved in a spatiotemporal world. What matters is not just *where* the fruit is located but where it is *when* it is ripe. Perception is filled with multimodal effects involving space and time. Cognition employs very similar measure concepts for both. The hippocampus utilizes place cells and time cells. It would be very surprising if two separate systems, one for time and one for space, evolved and appeared at such different times developmentally, given how tightly linked the two are in physics, biology, and psychology.

Two challenges for a dual system approach to temporal cognition

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Abstract

Hoerl & McCormack (H&M) propose a two-system account of temporal cognition. We suggest that, following other classic proposals where cognitive systems are putatively independent, H&M's two-system hypothesis should, at a minimum, involve (1) a difference in the nature of the representations upon which each system operates, and (2) a difference in the computations they carry out. In this comment we offer two challenges aimed at showing that H&M's proposal does not meet the minimal requirements (1) and (2).

Once upon a time, cognitive scientists employed the notion of "cognitive system" to put forth substantive hypotheses about cognitive architecture. There was much debate then as there is now as to what it takes for a certain system that causally brings about a behavior to count as cognitive, let alone what it counts for *two* such systems to be distinct (De Brigard 2017). Nevertheless, many would agree that at the very least, two postulated systems count as distinct if (1) there is a difference in the nature of the representations upon which they operate, and (2) they carry out different computations. These minimal requirements, for instance, undergird Atkinson and Shiffrin's (1968) model of a short-term memory system – involving temporally limited computations and modality-dependent representations – distinct from a long-term memory system, which involves modality-independent representations and no temporal constraints on computations.

Our concern here is that Hoerl & McCormack's (H&M's) proposal may not meet these two minimal requirements. To illustrate this point, we offer two challenges. The first challenge pertains to the temporal updating system (TUS). According to H&M, the TUS operates upon representations of how things are in the world *in the present*. This does not mean, however, that the representations of the TUS are not time-sensitive: They are, as they can be updated to convey information about change. Simply put, the representations of the TUS can represent change because change is part of the represent*ing*, not the represent*ed*. As such, H&M argue, a creature with just a TUS can still represent an object as desirable (e.g., a worm, a pacifier) even when it is no longer visible in its surroundings. Moreover, by being able to capture information about non-present but desirable objects, the TUS enables creatures to represent primitive goals.

But how does a creature know that a representation has been updated? Consider the case of, say, a scrub jay returning to a previously cached worm, as in the Clayton and Dickinson (1998) study. According to H&M's proposal, the scrub jay may decide to go for a worm rather than a peanut because the updated representation supplied by its TUS – unlike the representation of its current surroundings supplied by the perceptual system – represents the worm as an *open* possibility, that is, as a goal that is still available in the organism's future. By contrast, the scrub jay that goes for the peanut instead of the worm may do so because the TUS delivers an updated representation in which the worm is absent. Not only is this possibility *closed*, but this scrub jay is, presumably, no longer aware of its past existence. Their suggestion is that the modal profile of these scenarios is time-locked to the timing of the cache; indeed, H&M explicitly acknowledge that the TUS cannot handle updating that does not conform to the order in which the information was received. But there is plenty of animal research showing that whether an option is seen as available to an organism in the future is not clearly tied to the time in which it is learned. For example, rodents can return to prior less desirable choices (e.g., taking a long but likely open path in a maze) upon learning that a more desirable one (e.g., taking a short but likely closed path) is unavailable (Tolman & Honzik 1930). In other words, rodents seem to be able to revisit a previous option upon learning that what appeared to be an open possibility is, sadly, closed. The flexibility in the rodent's updated representations suggests that the modal profile—whether an option counts as an open versus a closed possibility – is not fully accounted for by the timing of learning, and further suggests that the animal is either capable of representing alternatives as being in a possible future or a possible past (a representational constraint not afforded by the TUS), or else is capable of drawing contrastive inferences between outdated and updated representations (a move that makes the computations of the TUS suspiciously similar to the temporal reasoning system [TRS]).

The second challenge pertains to the TRS. In their discussion of infant and preschool children, H&M argue that the TRS represents "times arranged in a linear array such that each time occupies a unique unrepeated location in the array" (p. 39). It is implied that such is the proper concept of time. However, there is currently cross-cultural evidence of non-linear ways of thinking about time, including – but not limited to – cyclical, branching, and volumetric (Casasanto & Boroditsky 2008). Are these non-linear ways of thinking about time still handled by the TRS? What about reasoning about time within the framework of the theory of relativity, whereby under certain conditions – which physicists have reasoned about – linearity breaks down? Are these improper concepts of time or are they concepts of time that are not handled by the TRS? Given that we can reason about time in all sorts of non-linear ways, we think that it may be unnecessary to postulate the existence of a dedicated TRS that only operates with a particular kind of temporal representation. A more parsimonious account may ask us instead to focus on how acquired information about linear time can be manipulated *in the same way* as acquired information about non-linear time, and in turn how such information can be used for reasoning. Under this lens, children learn to reason about time thanks to the development of the same representational, attentional, and memory systems that enable them to reason about all sorts of things, rather than through the maturation of an independently dedicated TRS. Furthermore, under this account, the intra- and cross-cultural heterogeneity in conceptions of time is explained by variations in acquired representations and inferential strategies, rather than competing TRSs.

In sum, we think that there is need for further argument as to how H&M's proposal meets the minimal requirements (1) and (2).

Nonhuman sequence learning findings argue against Hoerl and McCormack's two systems of temporal cognition

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Abstract

Hoerl & McCormack propose that animals learn sequences through an entrainment-like process, rather than tracking the temporal addresses of each event in a given sequence. However, past research suggests that animals form "temporal maps" of sequential events and also comprehend the concept of ordinal position. These findings suggest that a clarification or qualification of the authors' hypothesis is needed.

Hoerl & McCormack (H&M) propose that two systems guide behavior in time. Both human and nonhuman animals possess the "temporal updating" system; it forms an internal model of the world based on how events change across time. Through experience, the model becomes entrained to temporal patterns in the environment. When a sequence of events begins, the model is continuously updated in accordance with prior experience. If these updates coincide with changes in the environment, then the animal will act appropriately in time. Importantly, the dimension of time is not explicitly represented within the temporal updating system. Changes in the model simply determine the animal's current expectations, similar to how gravitational changes from the moon determine current ocean tides (cf. Killeen & Fetterman 1988). However, the "temporal reasoning" system is held to be uniquely possessed by humans; here, time is represented continuously and the temporal locations of events are explicitly tracked.

Overall, the proposal brings a useful perspective to key findings related to whether animals are "stuck in time" (Clayton & Dickinson 1998; Roberts 2002). Our primary issue with this hypothesis concerns claims about how humans and nonhuman animals engage in sequential learning. According to the authors, humans learn sequences by reasoning about the temporal relationships that separate events. However, nonhuman animals cannot represent the "temporal addresses" of prior events. Therefore, they must engage in sequential learning by being exposed to the events within a sequence in their "correct and full order," allowing the model to entrain to the sequence. The authors propose that this is a "signature limit" of the temporal updating system. Nonetheless, this claim does not comport with prior work.

For example, research suggests that nonhuman animals generate "temporal maps" of sequential events (Balsam & Gallistel 2009); that is, they represent time as a continuum and are able to arrange the temporal locations of events in a sequence along this array. This work parallels the less controversial claim that animals generate "spatial maps" of the environment that they use to remember the locations of objects in space.

Temporal map research is extensive and longstanding (Honig 1981; Matzel et al. 1988), but a simple experimental example runs as follows. During Phase 1, animals are placed into a conditioning chamber and repeatedly presented with two cues that are separated by a certain time interval (Cue A→Cue B). On a subsequent training day (Phase 2), animals return to the chamber and are presented with a reward that is followed soon after by the second cue from Phase 1 (Reward→Cue B). Importantly, the time interval separating reward and Cue B is arranged so that, in the context of Phase 1, reward *should have* occurred at a certain time between the cues (Cue A→Reward→Cue B). However, the animals never explicitly experience the full sequence in its appropriate order; they only experience misordered fragments of the full, "implied" sequence. Yet, animals appear to integrate the two learning episodes and behave according to the implied sequence. When given Cue A, they expect reward, despite never receiving reward after its presentation. Conversely, when presented with Cue B, they do not expect reward.

Various permutations of this basic design have extended this effect (Molet & Miller 2014), which we cannot detail for brevity. However, these experiments strongly suggest that animals not only order the shuffled fragments of an implied sequence, they also represent the continuous intervals that separate each event it contains (Molet et al. 2012; Taylor et al. 2014). In other words, animals represent the temporal locations of items within a continuous temporal map, much like they track the spatial locations of items within a spatial map. These findings are difficult to reconcile with the authors' claim that nonhuman animals should only be able to learn a sequence by explicitly experiencing every event within the pattern in its appropriate order.

A related line of work suggests that nonhuman animals understand the concept of ordinal position (Orlov et al. 2000; Orlov et al. 2002). In these experiments, animals learn the order of different lists of items (e.g., List 1: A1, A2, A3 / List 2: B1, B2, B3). Then, animals are simultaneously presented with items from one of the lists and are required to tap each in its appropriate order (e.g., first A1, then A2, then A3). Importantly, a distractor is also presented, composed of an item in one of the other lists (e.g., B2). Animals frequently tap the distractor. Importantly, they do so systematically, usually corresponding to the distractor's ordinal position within its own list (e.g., responding: A1→B2→A3, rather than the correct pattern: A1→A2→A3). Furthermore, if animals later learn novel lists containing items from initial training, they learn faster when each item maintains its previous ordinal position (e.g., new list: A1→B2→C3 vs. C3→A1→B2; Chen et al. 1997). Carefully controlled experiments have ruled out accounts of performance being solely based on rote long-term memory, working memory, and simple associative-linking processes. Again, these findings are difficult to reconcile with the claim that animals learn sequences by repeatedly updating an internal model as items are experienced across time.

Given the emphasis on sequential learning processes as a primary difference between the two systems, we were surprised that H&M did not address these findings. To be clear, we are not arguing that animals possess the temporal reasoning system. Associative explanations may adequately explain the above findings, albeit ones that cede a basic time representation to nonhuman animals (Arcediano & Miller 2002). However, representing temporal information does not necessarily imply that nonhuman animals are capable of mental time travel (for a discussion of this topic in relation to temporal maps, see Arcediano & Miller 2002) or even retain a timeline of life experiences. For example, after integrating two learning episodes during a temporal map experiment, does the animal still remember that the two learning episodes were experienced apart from one another? Or have they formed an immutable model of the implied sequence (with a time dimension) effectively "losing" knowledge of the component learning episodes? The work reviewed here does not speak to these questions. All of the reviewed work requires either a qualification or clarification of the authors' hypothesis.

Closing the symbolic reference gap to support flexible reasoning about the passage of time

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Abstract

This commentary relates Hoerl & McCormack's dual systems perspective to models of cognitive development emphasizing representational redescription and the role of culturally constructed tools, including language, in providing flexible formats for thinking. We describe developmental processes that enable children to construct a mental time line, situate themselves in time, and overcome the primacy of the here and now.

Hoerl & McCormack (H&M) distinguish temporal updating and temporal reasoning systems, but do not elaborate on how the temporal reasoning system develops. This commentary considers the extent to which the temporal reasoning system depends on language and other external representations in its development, while aiming to answer H&M's question of how to characterize temporal cognition in early childhood. As with numerical cognition (Núñez 2017), there appears to be a symbolic reference gap between a non-symbolic (updating) mode of information processing accessible to infants and a symbolic (reasoning) system that develops through explicit teaching and enculturation. We argue that this gap is overcome in childhood through piecemeal acquisition of verbal and visual-spatial means of explicitly representing and organizing notions of time.

Children's acquisition of language is inextricably linked with their expanding capacities to make sense of objects and events in the world. Words draw attention to things and their recurrent use invites children to search for underlying commonalities across referents and situations (Plunkett et al. 2008; Waxman & Markow 1995). For over 70 years, developmentalists have traced the emergence of temporal language through children's acquisition of grammatical aspect, tense marking, deictic expressions (e.g., *now, then*), and labeling of temporal patterns (e.g., days of the week) (Ames 1946; Wagner 2001; Weist 1989). As with other words, children are exposed to temporal terminology informally in social contexts and familiar routines. Such terms distinguish time based on arbitrary divisions (e.g., *minutes, hours*), natural cycles (e.g., *day, night*), social events (e.g., *lunchtime, Thanksgiving*), or sequences (e.g., *before, after*). Through conversational discourse, children gain familiarity with the corresponding concepts, although they may use terms in ways that do not fully reflect conventional meanings (Levy & Nelson 1994). For example, preschoolers may interchangeably use *yesterday* and *tomorrow* to refer to times *not today* (Harner 1975), indicating that their production of temporal vocabulary often precedes accurate comprehension.

Nelson (1985; 1996) proposed a dialectical model of language development in which children derive the meaning of words from their patterns of use in discourse contexts. She extended the model to children's acquisition of temporal concepts, theory of mind, and autobiographical memory, proposing that through social transactions with caregivers, children acquire conventional ways of structuring knowledge and gain flexibility in adopting varying and potentially conflicting perspectives on events (Nelson 1991; Nelson & Fivush 2004; Nelson et al. 2003). Caregivers' use of evaluative language, often delivered in the context of narratives, supplements children's script-like representations of events by imposing a causal-intentional framework for making sense of human behavior. As described by Tomasello (1999, p. 214), "Language is structured to symbolize in various complex ways events and their participants, and this is instrumental in leading children to 'slice and dice' their experience of events in many complex ways." Caregivers scaffold children's acquisition of temporal concepts by engaging children in conversations littered with sequence terms, conventional time markers, and references to the immediate past and future plans (Hudson 2002; 2006). Such markers help children track the activities of people (including themselves) over time, and therefore contribute to the emergence of a temporally extended self-concept.

Karmiloff-Smith (1979; 1992) similarly viewed conceptual development as embedded in interactive contexts, while emphasizing its intrinsic connection with the child's sensorimotor activity. In her theory of representational redescription, she aimed to account for the process by which the child's early proceduralized knowledge is redescribed into more explicit, abstract, and conventionalized formats. According to Karmiloff-Smith (1992), it is not language per se that is responsible for developmental change, but the redescriptive processes that allow implicitly represented knowledge to be flexibly re-represented in multiple formats (including language) that are increasingly accessible to consciousness and meta-cognitive reflection. Such symbolic formats include image schemas (Mandler 2004), generalized event representations (Nelson & Gruendel 1981), gestures (Goldin-Meadow 2003), drawings (Goodnow 1977), and other forms of visual-spatial notation that may be intermediary to the fully explicit representations assumed by H&M to underlie the temporal reasoning system.

In H&M's account, temporal reasoning requires the construction of a linear representation of time, where each time occupies a unique, unrepeated location. Núñez (2011) summarizes the culturally and historically mediated processes that led to the invention of the number line concept, with its left-to-right mapping of quantities onto a spatial representation where each number has a discrete location. Acquiring the number line concept would provide the child with an organizational framework for constructing a mental time line (Núñez & Cooperrider 2013). However, as noted by H&M, situating events in time is complicated by the ever-shifting present and our capacity to treat any moment as the "present" in a given discourse or narrative context. Hence, flexible perspective taking, which develops alongside theory of mind, may prove critical for shifting one's viewpoint away from the immediate here and now. H&M and others note considerable overlap in the frames of reference used in positioning objects and events across temporal and spatial domains, while acknowledging that representations vary considerably as a function of sociocultural and linguistic factors (Casasanto & Boroditsky 2008; Tenbrink 2007). As described by Núñez and Cooperrider (2013, p. 220), "Time is not a monolith, but rather a mosaic of construals with distinct properties and origins." Similar to language (Tamariz & Kirby 2016), temporal representations may become conventionalized through processes of cultural transmission, and therefore may not be universal.

H&M note the substantial challenge of accounting for the developmental emergence of the temporal reasoning system. We believe that acknowledging the co-existence and diversity of representational formats lessens this concern. The child's ability to reason about time capitalizes on available representational formats, which include the clock and calendar systems formally taught in school (Burny et al. 2009). Such formats represent time in publically accessible ways, and therefore allow it to become an object of contemplation and negotiation. Although details remain to be worked out, especially with regards to individual differences in developmental trajectories, there is growing consensus that language and other symbolic reference systems mediate cognitive development, ultimately serving to extend cognition by offloading processing to external media (Clark & Chalmers 1998).

Beings in the moment

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Abstract

Hoerl & McCormack's theory defines temporal behavior from an awareness of time, but lacks one critical element: the impact of "psychological presence" in the "moment now." Central to experience of temporal non-stationarity: "Nowness" links future with past in the context of time flow. Does this differ between species? Evidence suggests not: Different temporal experiences between species requires greater critical evaluation.

Husserl (1917/1991) and Bergson (1910) considered the experience "of time" to be related to experience "in time." Within this conceptualization, the immediate present, the "moment now," is a composite of future with the immediate past (Husserl 1917/1991). Beyond this, real time, as in experience of an enduring and continuous flow of events from future toward the past, is not directly knowable, but may be judged through intuition arising from a series of acts of direct participation in immediate experience. This intuition Bergson (1910) referred to as "lived time," and this describes a continuous experience of the moment now, influenced by its context of past events, while influencing and perhaps influenced by the likelihood of events occurring in the future.

By these conceptualizations, the moment now is the nexus for past and future, with experience of "nowness" including both past and future events. Seminal scientific investigations of the "psychological moment" were undertaken in early schools of theoretical biology, such as that of von Uexküll (1928; 1934, translated as von Uexküll [1957]). From Uexküll's school, experimental work was published in the 1930s, using near-identical experimental techniques to delimit the minimal psychological moment of various creatures: human beings, fighting fish, and snails (Brecher 1932). While the duration, or "quantum" of the moment, differed across species, in all of the species studied, Brecher found that events separated by time might, given short intervals between their presentations, be combined to form a meaningful, co-existent experiential content in the now.

Although Brecher showed that both animals and humans could provide an estimate of the experience of present co-existence using similar experimental techniques, he also showed that this experience related to the "content" of the temporally separate, but experientially coincident events, at least for the fighting fish. These animals experienced repeated exposures to the image of a conspecific, viewed through slits cut at right angles to one another in a rapidly rotated disk. Above a certain exposure frequency (equivalent to around 30 Hz), the successive images fused to form a continuous image, at which point the fish attempted his attack. Two points can be taken for this example. First, insofar as psychological presence includes content provided by the fusion of temporally separated events, this content may be meaningful. At least, and for creatures other than humans, past and present are meaningfully unified into an experience of nowness. The second point refers to Uexküll's concept of *Umwelt* or "meaningfully relevant aspects of the environment." Ultimately, *Umwelten* determine the sensory, perceptual, and subsequent physiological responses of the animal, and insofar as the moment is an index of basic cognitive capacity (i.e., the amount of information we can process in the smallest interval of psychological time), the complexity of Umwelt responses, and so Umwelt itself, determines a given species moment quantum.

This second point entails psychological presence to be equated not with the experience of time flow, but with the "content structure" of experience – in this case the meaningful content of a given moment. Consequently, and based upon representational states related to event structure in time, all animals should be considered the same because they should be considered to be located on the same experiential continuum. Uexküll was clear that whereas moments may be related to relevant aspects of the environment to which the animal responds, this in turn refers to the number of (coordinated) reflex arcs in the animal's behavioral repertoire. Uexküll rejected the reflex arc as sufficient to explain either the response or the cognitive organization underlying the response. In fact, this may be better conceived of as a form of capacity limit, which may be indexed by the duration, and therefore in the content, of the moment. Consequently, the moment, insofar as this links past and future, is determined by the meaningful interaction of the animal with its environment.

Therefore, and as a modification to Hoerl & McCormack, I propose temporal updating as insufficient to describe all common aspects of temporal experience across species. Instead, at least the meaning of events and the meaning of the response to those events link the past and present, at the most elementary level of temporal experience. To the best of my knowledge, there are no data to support an extension of this idea into the relationship between past, present, and future events, but it leaves this possibility open. Further, there is no evidence linking what occurs at the most elementary level of temporal experience to quanta in the hundreds of seconds or even second time ranges. However, the absence of data is not conclusive evidence, whereas, at least in humans, there is evidence that performance on time estimation tasks scale almost linearly with an exponent close to 0.9 (Eisler 1976). If humans and animals differ only with reference to the duration of their moments and what constitutes relevant experience in time, given identical operating characteristics in the brain, there is no reason to suspect any difference in the scaling function that describes their experience in time.

However, the issue raised by the representation of temporality in different species does not end with this point. Uexküll noted that some species, in this case the sea urchin, possess multiple independent reflex arc systems. This means these animals might experience multiple, but nonetheless, concurrent experiences of Umwelten in time. We tend to assume all temporality to be the same as out temporality, that is, a one-dimensional state in which events proceed, sometimes at varying rates, from future to past. However, this may not be the case. Additionally, and as argued earlier, across species, the qualitative content of Umwelten, as well as the timing of the moments within which they present, and the nervous systems within which they are instantiated (their quantitative aspect) are different. Given we neither experience the world as animals do, nor are we able to experience multiple concurrent experiences of time, we may also be unable to conclusively define a model that adequately describes experience in time for any species except our own.

Locating animals with respect to landmarks in space-time

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Abstract

Landmarks play a crucial role in bootstrapping both spatial and temporal cognition. Given the similarity in the underlying

demands of representing spatial and temporal relations, we ask here whether animals can be trained to reason about temporal relations by providing them with temporal landmark cues, proposing a line of future research complementary to those suggested by the authors.

Hoerl & McCormack (H&M) offer a two-system account of temporal cognition, arguing that only humans evolved a second, more advanced system, which allows reasoning about temporal relations. This view falls into a tradition of views on human uniqueness traceable back to at least C. Lloyd Morgan (1903) and perhaps even to Aristotle (Sorabji 1993), who held that the representation of relations is a uniquely human cognitive achievement (Clatterbuck 2016). Morganian skepticism can be applied domain-generally (Penn et al. 2008) or only to relations in a particular domain, such as meta-cognition (Carruthers 2009). H&M seem to offer a version specific to temporal cognition, arguing that whereas animals can represent objects and properties that they encounter at different times in a maplike representation of their environment, they cannot represent those events as occurring at different times in a systematic way.

A generic strength of Morganian skepticism is that nonrelational cognition has intuitively clear signature limits. This is where H&M's view shines; in particular, they suggest that animals cannot learn information about events in an order other than that in which those events actually occur. Morganian skepticism, however, faces a generic challenge. After conceding to animals the representational flexibility required to explain their flexible behavior, it becomes difficult to explain why they cannot learn to represent relations. The boring answer to this question – boring because it renders all other cognitive differences between humans and animals derivative from the most obvious one – is that representing relations requires language, and animals lack language. The challenge facing H&M is particularly tricky, for they seem to concede that nonlinguistic animals possess mechanisms to represent spatial relations. Here, we ask why these mechanisms could not be bootstrapped to represent an additional temporal dimension as well, albeit less precisely than humans do so with temporal language.

To put some pieces on the workbench, let us briefly explore how animals might represent spatial dimensions. In mammals, at least, the most popular story has to do with the way that place cells and grid cells in the medial temporal lobes cooperate to build a maplike representation of their environment (Moser et al. 2008). Skipping over many details, place cells represent locations by binding together snapshots taken from different viewpoints in the same spot, and grid cells represent the locations of these bundles with respect to one another in spatial dimensions by linking them to a spatially organized array. Visible landmarks probably play an important role in establishing these links. The grids are anchored by landmarks, and the same landmarks are visible from different egocentric viewpoints.

To introduce a new component to the conversation, some psychologists have argued that temporal landmarks play a similar role in anchoring a system of temporal representation in children (Shum 1998; Tartas 2001). Children may start by placing events with respect to an especially memorable life transition ("before I started preschool," "after we moved to the new house"), and then begin placing events in an order with respect to a few indices sequenced by major events like birthdays ("when I was 3," "when I was 4"). Only later, after learning more ordered sequences of temporal landmarks, can they progress to a series of hierarchically nested indices that enable the level of fine-grained, monotonically ordered temporal representation that characterizes adult human cognition (times of the day, days of the week, months of the year, and so on [Jack et al. 2016]). Neuroscientific and psychological evidence further supports the idea that some of the mechanisms that represent spatial relations can be redeployed to represent temporal relations as well (Casasanto & Boroditsky 2008; Eichenbaum 2017).

This view on development in humans suggests a different perspective on the human-animal divide in temporal cognition. These structural and functional parallels make it fairly plausible that some animals that use spatial landmarks might thereby possess mechanisms to use temporal landmarks, too (Buzsáki & Moser 2013; Ekstrom & Ranganath 2018; Naya & Suzuki 2011). However, we might attribute the absence of human-like levels of temporal systematicity in animals not to the monolithic inability to represent temporal relations, but rather to the comparative scarcity of temporal landmark cues in animals' lives. Animals live shorter lives with brief neotony and fewer stark autobiographical transitions, and without language, it is harder to provide animals with temporal landmark cues at learning or recall. In short, rather than animals failing to *evolve* a temporal reasoning system because they would not need it, perhaps it is instead because they typically fail to *develop* one, despite possessing the requisite neural machinery, because they are not exposed to enough of the necessary scaffolding.

This alternative perspective also suggests a different tack for future research. Before putting animals in experiments that test their ability to deploy temporal relations, we should expose them to temporal landmarking cues that could let them place events as occurring before or after the landmark, and provide them with tasks where they would be rewarded for ordering those events with respect to those landmarks and, consequently, each other in systematic and novel ways. The generic challenge facing this response to Morganian skepticism is that the landmark cues must not simultaneously provide animals with information about repeatable abstract properties of their world that have been previously rewarded with outcomes that could allow them to independently solve the task. This is a very difficult experimental challenge, but one not so different from similar difficulties in other domains that have already been overcome, for example, providing animals with evidence of mental relations without providing confounding behavior-reading cues (Bugnyar et al. 2016; Karg et al. 2016; Penn & Povinelli 2007). This might mean that we should focus on temporal cues that are associated not with things like times of day or seasons, which recur and carry many associations to rewarded outcomes themselves, but rather to personally significant events that may occur only once in an animal's life, such as a dominance reversal in a social hierarchy or movement to a new enclosure.

Future-oriented objects

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Abstract

Hoerl & McCormack suggest that saving tools does not require temporal reasoning. However, we identify a class of objects that are only possessed (i.e., saved) in anticipation of future needs. We propose that investigating these future-oriented objects may help identify temporal reasoning in populations where this ability is uncertain.

Umbrellas are for the future. Most of the time it is not raining, so umbrellas are useless and just take up space. They only become useful when it rains, and this will happen in the future. Other objects are also like this. Band-Aids only become useful when someone gets cut, fire-extinguishers only become useful when something accidentally catches on fire, and so on. These future-oriented objects prepare us for rainy weather, cuts, and fires that may arise in the future (and do not yet exist in the surrounding environment). Hence, temporal reasoning is required to know that one should own and keep the artifacts needed to deal with these future situations. An agent unable to anticipate future events would not bother owning an umbrella or any other future-oriented possessions.

The observation that some objects are future-oriented was inspired by Hoerl & McCormack's (H&M's) claim that tool-saving tasks (Kabadayi & Osvath 2017; Mulcahy & Call 2006) do not assess temporal reasoning. In these tasks, an agent appears to show future-thinking when an agent appears to show future-thinking when selecting a tool for use at another location (e.g., picking up a rock in one location so that it can later be used to obtain food elsewhere). H&M convincingly suggest that tool saving does not require temporal reasoning, and may instead depend on the atemporal understanding that the saved tool is useful somewhere else in the current environment. This analysis, however, led us to reflect that for future-oriented objects, like umbrellas, tool saving *does* require temporal reasoning.

Examining tool saving and use of future-oriented objects may help provide evidence of temporal reasoning in populations where this ability remains uncertain, such as preschoolers. As H&M note, temporal reasoning is well established in 5-year-olds, but the abilities of 3-year-olds remain in doubt (Atance et al. 2015; McCormack & Atance 2011). Indeed, 3-year-olds consistently fail tasks that require them to select an object in anticipation of a future need, such as needing a box to reach a game table (Russell et al. 2010), a key to open a box in another room (Suddendorf et al. 2011), and an item to alleviate boredom during an otherwise uneventful period (Atance et al. 2015; 2017; Metcalf & Atance 2011; Suddendorf & Busby 2005).

However, we see a different pattern of results when 3-year-olds are asked about future-oriented objects, though no study has done so exclusively. In one study, Atance and O'Neill (2005) asked children to select objects to take on a future trip, and to justify their selections. Although 3-year-olds referenced the future in only 37% of their explanations overall, they did so 70% of the time when justifying their selection of Band-Aids – the only future-oriented object included. In another study, Atance & Meltzoff (2005) asked children to select appropriate items to take on imaginary future excursions. Again, Band-Aids were included as a possible item to take for a walk through a rocky stream, and 3-year-olds selected this object more often than chance and as often as older children (though they did so only when a semantically related distractor item was not present). When asked to justify this selection, 3- to 5-year-olds referenced the future in 75% of their justifications. Though these findings are encouraging, they are admittedly narrow in scope and must be interpreted cautiously. A study exclusively exploring children's beliefs about future-oriented objects would provide us with deeper insight into their temporal cognition, as a full understanding of the function of such objects necessarily involves consideration of the future.

Future-oriented objects may also be relevant for attempts to infer the cognitive abilities behind prehistoric artifacts (i.e., cognitive archaeology [Coolidge & Wynn 2016]). Scholars have suggested that even the makers and users of Oldowan tools, which date back more than 2.5 million years, were capable of temporal reasoning and could anticipate future needs (Osvath & Gärdenfors 2005; Shick 1987; Suddendorf & Corballis 2007a; see Toth & Schick 2018 for an overview). These claims often concern tool saving. For example, Oldowan hominins transported stone tools far from the locations where they were created, transported stones and other materials to accumulation sites (which may have served as caches), and may have carried stones to hunt prey they encountered. H&M's analysis suggests that these forms of tool saving might not have required temporal reasoning. For example, rather than carrying tools for use in the future, Oldowan hominins may have viewed themselves as carrying tools for use *elsewhere*. But this conclusion may hinge on whether some Oldowan tools were future-oriented objects. A stone for throwing at prey is not a future-oriented object if the hunter knows the prey is already somewhere else in the current environment. But a tool specialized for butchering carcasses may be future oriented (assuming it is intended for hunted, rather than scavenged, animals). The maker may have to anticipate that an animal must be successfully hunted before the tool can be used.

We have suggested that temporal reasoning likely underlies keeping possessions that prepare one for future events. Other kinds of saving may also require temporal reasoning. Consider the act of saving raw food to be cooked. Great apes prefer many types of food when they are cooked rather than raw (Wobber et al. 2008), and given experience with cooking, chimpanzees will bring raw food to a cooking device and wait for it to be cooked (Warneken & Rosati 2015). Chimpanzees are unlikely to view these activities as necessary for securing a reward that is currently somewhere else in its environment. Before the food is cooked, the reward does not yet exist. Hence, saving raw food probably indicates the ability to anticipate the future situation of cooked food being available (see Beran et al. 2016 for an alternative associative-reasoning explanation). Anticipating that objects will change in the future is also necessary to understand many other aspects of the world, including agriculture (e.g., seeds will grow into plants) and crafting (e.g., clay will harden, paint will dry).

Timers from birth: Early timing abilities exceed limits of the temporal updating system

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Abstract

Hoerl & McCormack argue that children are incapable of reasoning about time until age 5. However, their dual timing perspective does not address non-symbolic timing, or timing in the absence of symbols/language. Given substantial evidence that infants and children are capable of non-symbolic timing, I argue that infants and children are well-tuned timers prior to age 5.

Hoerl & McCormack (H&M) present a dual timing theory through which they claim that children are incapable of reasoning about time until the age of 5, when the temporal reasoning system becomes available. The proposed dual timing system, however, neglects a significant body of literature detailing timing in the absence of symbols and/or language (i.e., non-symbolic timing; Meck & Church 1983; vanMarle & Wynn 2006; Odic, 2018; Odic et al. 2016; for a review in animals, see Gibbon 1977). By ignoring this body of evidence, the authors greatly undermine infants and children's timing abilities. In particular, substantial research reveals both infants and children are able to track durations non-symbolically (Brannon et al. 2007; Droit-Volet & Wearden 2001; Hamamouche & Cordes 2019; Odic 2018; Provasi et al. 2011; vanMarle & Wynn 2006). Contradicting the proposed temporal updating system, I first describe non-symbolic timing as the most basic form of timing. In doing so, I also unveil infants and young children's impressive non-symbolic timing abilities.

Although I agree that the temporal reasoning system, which supports our mental representations of temporal symbols (linguistic labels, units of measurement, etc.), is not available until later in development, a substantial literature suggests that from birth we are able to represent time non-symbolically (Brannon et al. 2007; Odic 2018; Provasi et al. 2011; vanMarle & Wynn 2006). Our non-symbolic representations are very approximate and do not require any linguistic information. To test non-symbolic representations of time, participants are often asked to discriminate between two unique durations. For example, participants may decide which of two stimuli were displayed longer or which of two sounds lasted longer. To succeed in this task, participants should be tracking time. Other tasks, such as deciding whether a novel duration is more similar to a short or long standard duration (i.e., bisection tasks), also assess non-symbolic timing abilities (Church & Deluty 1977; Meck & Church 1983). Given H&M's proposal, it is unclear how the dual perspective on timing would accommodate non-symbolic timing abilities. In particular, the proposed temporal updating system, which H&M describe as the most basic timing system, could not support performance on non-symbolic timing tasks. This is particularly noteworthy given that many researchers believe non-symbolic timing to be the most basic form of timing.

Moreover, according to H&M, infants and children under the age of 5, who are incapable of reasoning about time, should not succeed in non-symbolic timing tasks. Counter to H&M's proposal, however, young children are quite capable of making temporal judgments prior to the age of 5. For example, children as young as 3 show ordered performance on temporal bisection tasks. That is, as the duration increases, children become more likely to identify the novel duration as being more similar to the long standard duration (Droit-Volet & Wearden 2001). Relatedly, after learning a single standard duration (e.g., 4 seconds), 3-year olds are capable of discriminating the learned duration from a novel duration (e.g., 2 seconds [Droit-Volet et al. 2001]). Although children's non-symbolic timing abilities become more precise with age (Odic 2018), these data indicate that young children are fully capable of making temporal judgments.

Even more impressive is research demonstrating infants' ability to time non-symbolically (infants: Brannon et al. 2007; Provasi et al. 2011; vanMarle & Wynn 2006; children: Droit-Volet & Wearden 2001; Odic 2018). Using a bisection task, Provasi et al. (2011) discovered 4-month olds were capable of discriminating unique durations. First, infants heard a short sound (500 ms), followed by an image on the left side of the screen and a long sound (1,500 ms), followed by an image on the right side of the screen. In other words, infants were trained to look left when they heard the short duration and right when they heard a long duration. Then, during the test trials, infants heard intermediate durations (750 ms, 1,000 ms, 1,250 ms), and the direction of their first look was recorded, which the researchers interpreted as the infants' indicating whether the duration was more similar to the short or long standard value. If infants were unable to detect differences in the durations, they should have looked equally to the left and right. Yet 4-month-olds showed a greater preference for the long standard duration as the duration increased. Using a different paradigm, Brannon et al. (2007) also found infants were capable of non-symbolic timing. Here, infants were habituated to a cow opening its mouth for a certain duration. After the baby had habituated (was no longer interested in the cow's movement), the cow opened its mouth for a new duration. Again, if infants were unable to detect the change in duration, their looking time should stay consistent upon seeing the cow open its mouth for a novel duration. Contrary to this, 6-month olds' looking time increased upon observing the cow's mouth opening for the novel duration, indicating that they noticed the change in duration. This finding has not only been replicated (vanMarle & Wynn 2006), but also extended to include changes in neural responses during timing tasks in both infants and adults (Brannon et al. 2004; 2008).

In sum, the proposed dual timing system neglects non-symbolic timing abilities, a process that would not be supported by H&M's temporal updating system. In doing so, the authors suggest that infants and children are incapable of representing time until the age of 5, when the temporal reasoning system becomes available. I contend, however, that the temporal updating system does not fully account for basic timing abilities and, therefore, unfairly discredits infants and children as well-tuned timers.

Temporal updating, behavioral learning, and the phenomenology of time-consciousness

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Abstract

Hoerl & McCormack claim that the temporal updating system only represents the world as present. This generates puzzles regarding the phenomenology of temporal experience. We argue that recent models of reinforcement learning suggest that temporal updating must have a minimal temporal structure; and we suggest that this helps to clarify what it means to experience the world as temporally structured.

Hoerl & McCormack (H&M) argue that mature humans rely on a temporal reasoning system to represent particular times, temporal order, and tense. By contrast, they claim that nonhuman animals and human infants rely exclusively on a temporal updating system, which represents change by replacing one atemporal representation with another. As H&M note, this entails that human infants and nonhuman animals only represent the world as present. We find their dual systems approach promising. But we are apprehensive about their claim that temporal updating utilizes only atemporal representations; this claim generates puzzles for the phenomenology of temporal experience, and it conflicts with the most promising models of behavioral learning.

There are difficult philosophical questions about how the experience of temporality or flow is related to the structures that produce such experiences (Ismael 2017). One common way to account for the temporality of conscious experience is by arguing that each momentary phase includes a trace of the previous experience and an anticipation of what is about to occur (Husserl 1917/1991). It is claimed that these retentive and anticipatory features make the unification of conscious experience and the continuity of experienced objects possible. If a moving object were experienced only as present, each momentary state would feature a static object, with nothing to bind these states together as an experience of ongoing motion (Gallagher 2013). Likewise, if the temporal parts of an object were viewed sequentially and statically, there would be nothing to integrate them into an experience of a unified object. Finally, if an infant could not track its recent behavior, while orienting toward a future state, their sensorimotor capacities (e.g., hand-mouth coordination) would go unexplained (Gallagher 2011). But if traces of the immediate past and anticipations of the immediate future are intentionally available in our present experience (Thompson 2007, p. 320), it becomes easier to see how sequences of momentary experiences are organized to yield the experience of succession and duration. Temporally extended objects are experienced as persisting across multiple phases of a conscious process. Change occurs when there is variation across a process. And we experience surprise when a process fails to unfold as we expect it to.

Focusing on perceptual phenomena, Hoerl (2013a; 2013b) argues that experienced movement and change can be explained by successive relations between an organism and worldly events, because worldly events already have the requisite temporal structure. Philosophical considerations and data from psychophysics provide some support for this extensionalist proposal. However, considerations from the literature on reinforcement learning suggest that goal-directed behavior also requires cognitive processes that track the temporal dynamics of the world (cf. Petter et al. 2018). Sometimes, animals track evidence that *now* is a good time to forage; sometimes they recognize that *a current situation* is risky; and sometimes, they track the succession of different actions that will *eventually* lead to the acquisition of a reward. And in each of these cases, expectations about which actions will be followed by reward are fundamental to survival. And this means that animals need some way to contextualize momentary models of the world within dynamic and unfolding cognitive processes.

As H&M argue, a raven could represent an apparatus as something that "can be opened with a tool," and a tool as useful for a non-present task, without engaging in temporal reasoning. But doing so would require representing these objects as persisting, representing these actions as part of temporally extended events, understanding their relative value, and deciding whether to act on the basis of this information. Over the past two decades, several solutions to this representational problem have emerged. Model-free systems compute forward-looking predictions, track discrepancies between experienced and predicted rewards, and adjust future predictions to accommodate such discrepancies. Model-based strategies store a model of the world that specifies when a sequence of actions is expected to yield reward and compute decisions on this basis. Finally, recent models relying on successor representations suggest an intermediate class of systems that cache "long-term predictions about the states it expects to visit in the future" (Momennejad et al. 2017, p. 681). Following H&M, each of these capacities can be implemented by a system that dynamically updates its models of the world in light of new information. But each kind of system relies on forward-looking *expectations* about which actions are likely to be rewarded, as well as retained representations of what has worked in the past (Niv 2009); moreover, given the dynamics of our world, these expectations must be sensitive to temporal differences, as well as temporal relations between stimuli (Gershman et al. 2014; Luzardo et al. 2017; Petter et al. 2018).

Precisely how violations of expectations are experienced is a difficult matter, which we cannot address here. However, on the assumption that cognition frequently unfolds in the service of guiding action, most animals should possess the capacities required to track where they are in various ongoing processes, anticipate the evaluatively significant aspects of their actions, and adjust their behavior where things do not go as planned. Furthermore, when they update their models of their world, they should do so in ways that evoke changes in retentive content as well as changes in expectations. H&M could accept this form of temporal directionality by adopting a position midway between the phenomenologically grounded perspectives discussed above and the hypothesis articulated in the target article. Such an approach would permit a gap between mature forms of temporal reasoning and temporal updating; but instead of decomposing representations of processes into representations of states, it would focus on cognitive representations of events. And because events have a minimal temporal structure, it would be well poised to organize and integrate these representations in a way that would yield an experience of temporal flow. Consequently, this would yield a dual systems hypothesis that could account for considerations regarding both experience and behavior. This seems like a minimal amendment, as every cognitive state that spans a short interval is "embedded in a psychological context with very long scope, both in the forward and backward direction" (Ismael 2017, p. 25).

Updating the dual systems model of temporal cognition: Reasoning with dynamic systems theory

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Abstract

This commentary construes the relation between the two systems of temporal updating and temporal reasoning as a bifurcation and tracks it across three time scales: phylogeny, ontogeny, and microgeny. In taking a dynamic systems approach, flexibility, as mentioned by Hoerl & McCormack, is revealed as the key characteristic of human temporal cognition.

Temporal updating and temporal reasoning are suggested as a dual system for thinking in and about time by Hoerl & McCormack (H&M). However, the authors do not state explicitly in what relation these two systems stand. They only state that temporal updating is an older, more primitive system that serves as the basis for various kinds of temporal behavior in animals and humans and temporal reasoning is a novel, elaborate system reserved for adult humans.

Here, I examine this relation from a general dynamic systems perspective on three relevant time scales – phylogenetic (informed by comparative studies), ontogenetic (informed by developmental studies), and microgenetic (informed by studies on adult humans) – and point out critical issues that are open to empirical and/or conceptual debate. Tracking the relation between the two systems across multiple time scales results in a richer and more integrated view on the nature of that relation in terms of a common dynamical principle: bifurcation.

Phylogeny

H&M state that whenever animals update their current model they become oblivious to their earlier model of the world. This statement is rather perplexing, as if animals cannot recall previous states of the environment once it changes. When it comes to temporal behavior, humans and animals are basically on the same page. Not only is temporal behavior in animals characterized by the same laws of psychophysics, for example, scalar invariance (Buhusi & Meck 2005; Wearden 2016), animals also extract more abstract, namely ordinal or even algebraic patterns, from sequences of events (Dehaene et al. 2015). This evidence reminds us not to underestimate their temporal abilities. However, it is not detrimental to H&M's major point that animals lack temporal reasoning, because on this level, time need not be represented explicitly.

Ontogeny

H&M describe a tripartite developmental sequence that children pass through: from (1) temporal updating (3 years) over (2) an intermediate phase where they roughly distinguish present from past and future (4 years) to (3) temporal reasoning about proximal and distal past and future events located at specific points on an extended temporal dimension. How might children extract such an abstract dimension from their temporal experience in the world? Representational redescription (Clark & Karmiloff-Smith 1993; Karmiloff-Smith 1994) may be the answer, that is, the spontaneous tendency of children to progressively explicate the implicit format of knowledge such that it becomes available for explicit reasoning to the general cognitive system. Representational redescription of temporal information implies different levels of increasing decontextualization – from full immersion in time to abstract reasoning about time. This process can be framed as bifurcation of a unitary system into a multilevel hierarchy. This makes ontogeny probably the most exciting time scale because it is the same child that at one point in his or her development is (still) stuck in time, then undergoes bifurcation and emerges from it as a deliberate cognizer enjoying temporal reasoning. In this process, the acquisition of tensed language may support tensed thought. Language as a symbolic code has the potential to equalize the indirect experience of past and future events vis-à-vis the direct experience of present events (Ünal & Hohenberger 2017). Equally abstract (temporal) words and grammatical forms (tense, aspect) are used to refer to them.

Microgeny

The need for clarifying the relation between temporal updating and temporal reasoning becomes most pressing in adults because they avail of and use both systems, synchronously, in their daily behavior. How do they interact? Obviously, adults neither only temporally update nor only reason temporally. It is rather characteristic of us that we do both, at various times. The key feature that H&M mention in this context is *flexibility*. Through temporal reasoning, adults can arrive at the proper result even if novel information does not arrive in the original order of the event sequence. More generally, flexibility means that the two systems can be applied freely according to situational demands/constraints. This flexibility comes for free, enabled by the common self-organizing principle of bifurcation. H&M invoke bifurcation only at one point – when it comes to construing the (conscious) decision process of an adult choosing how his or her life shall temporally unfold in the future – in this or that direction. However, bifurcation is the general process behind the other (though unconscious) phylogenetic and ontogenetic changes as well; the change from the animal to the young child (that can only roughly distinguish present, past, and future) and the change from the young to the older child (that can distinguish increasingly better between any point in the proximal and distal past and future). Each time a further choice is enabled, a novel opportunity for the cognitive system to engage with temporality.

Last, I am concerned with H&M's characterization of the two contradictory elements of the "naïve theory of time": on the one hand, the exclusive "now," and on the other hand, the inclusion of the many nows into the overall flow of time. Already Husserl (1917/1991) recognized the oxymoronic characteristic of the now as "standing-streaming" (Kelly 2008). Each now is standing while all nows are streaming. Husserl argues that the nontemporal phenomenal experience of the now (as standing) is necessary for a stable time consciousness to arise in the first place. Yet the now is not concluded. It contains in itself a little bit of the future and a little bit of the past. These extensions Husserl dubbed "protention" and "retention," respectively. One may conceive of them as "time buds" from which the full temporal dimension may extend later on.

In conclusion, I have argued that the relation between H&M's two systems of temporal cognition may be conceived of as the result of a common principle of self-organization: bifurcation. Such a dynamical perspective helps integrate common observations across the phylogenetic, ontogenetic, and microgenetic time scales, as well as across species. Finally, it allows posing research questions whose determination is empirical.

Limitations of Hoerl and McCormack's dual systems model of temporal consciousness

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Abstract

Hoerl & McCormack's dual systems framework provides a new avenue toward the scientific investigation of temporal cognition. However, some shortcomings of the model should be considered. These issues include their reliance on a somewhat vague consideration of "systems" rather than specific computational processes. Moreover, the model does not consider the subjective nature of temporal experience or the role of consciousness in temporal cognition.

Hoerl & McCormack (H&M) propose a dual systems framework of temporal cognition. Although we appreciate the effort put forth by the authors, we are concerned with the foundations on which the model is built. One major issue is their choice of a dual systems rather than a dual process framework. Another issue is the overgeneralized relationship between temporal cognition and perception of change. To address some of these concerns, we offer that the model could be extended to include consciousness.

H&M choose to describe temporal cognition as consisting of two dissociable systems: temporal updating and temporal reasoning. The temporal updating system is a primitive system that represents only the most recently experienced state of affairs with no record of what came before. Time is not represented in this system; when a change from what was previously represented is detected, the new information replaces the old information, which is lost. On the other hand, time is explicit in the temporal reasoning system, which represents various states of affairs and the time at which they occurred. In our view, the appeal to two systems is overly broad; the evidence H&M present is compatible with two "processes," rather than two "systems" (Evans & Stanovich 2013). They do not refer to any specific mechanisms into which these putative systems could be reduced. Furthermore, H&M's model cannot be linked or decomposed into neural elements that can be empirically tested to ascertain the independence of the two systems they propose. This point is important because temporal updating and temporal reasoning can be manifested from multiple physical states, properties, and events (cf. the philosophical thesis of "multiple realization," Polger & Shapiro 2016); without knowing which ones, conclusions about systems are premature.

A second issue is that H&M assume that perception of change underlies temporal updating, emphasizing that change is necessary for an organism to update representations of how things are in its environment. However, we submit that the relationship between perception of change and temporal updating is mediated by consciousness. Consciousness is not explicitly considered in H&M's model, even though it has been shown that consciousness and psychological time are necessary for one another to occur (e.g., Berkovich-Ohana & Glicksohn 2014; James 1890). To illustrate, imagine a Ganzfeld environment in which the sensory experience is uniformly maintained. Despite the absence of environmental and external sensory input, participants are still able to temporally update and experience the passage of time (Glicksohn et al. 2017). The subjective experience is made possible here, not by environmental changes, but by awareness of internal events (e.g., heart beat and rhythm). Another example of the role of consciousness in mediating the relationship between perception of change and temporal updating is binocular rivalry, where two very different visual stimuli are presented to the two eyes simultaneously (Alais & Blake 2005). The brain detects the difference between the two stimuli and resolves the rivalry outside of awareness. At the conscious level, two images are not seen simultaneously, but sequentially in alternation, as the rivalry is resolved differently over time. Such experience of binocular rivalry implies perception of change and time passage. Without consciousness, neither one is possible. Therefore, consciousness must be considered in any model of temporal processing.

Both content and state aspects of consciousness should be considered in future models of psychological time. Examples of how content plays a role in time perception are evident in various temporal distortion cases. For example, the perceived duration of an object varies with its perceived spatial location: in a prismatic adaptation task, an object centrally located at the retinotopic level is perceived as located outside of central vision. The crucial result is that the perceived duration of the object varies with the perceived location, even though the actual display duration is equal (Isham et al. 2018). This suggests that spatial and temporal information are cognitively integrated to form the content of the temporal experience. In another example, the subjective moment of action in a racing game varies with performance feedback (winning or losing). Unbeknownst to the participants, performance feedback is arbitrarily chosen and delivered by a computer. Subsequently, participants judge the timing of action as earlier if they are told they have won (i.e., "If I won, then I must have pressed the button sooner") and later if they are told they have lost (Isham et al. 2011). The results support the perspective that temporal reasoning is affected by the contents of consciousness.

The state of consciousness also plays an important role in time perception. When a conscious state varies, psychological time is experienced differently. For example, time dilation is experienced when an organism is aroused (e.g., threat, van Wassenhove et al. 2008), or experiences heightened consciousness (e.g., during meditation, Kramer et al. 2013). Temporal duration also fluctuates in altered states of consciousness (e.g., near-death experiences, Wittmann & Paulus 2008). In short, temporal cognition is greatly impacted by different states of consciousness.

Given these shortcomings of H&M's model, we propose that a *dual process* framework is more suitable than a *dual systems* framework at this point in our understanding of temporal cognition. We also urge that research be directed to discovering the underlying neural substrates that characterize temporal updating and temporal reasoning. In this manner, the scientific goals associated with dual process theories would help frame an examination of the mechanisms of temporal cognition (cf. Evans & Stanovich 2013). In addition, given that H&M's model provides an overly substantial and general claim about change and temporal updating being closely related, we propose that the emphasis on change alone should be reconsidered. Last, we urge that consciousness be considered in models of temporal cognition as it is directly relevant to both change and the sense of time. We believe these suggestions may help strengthen H&M's current model and inform future theories of temporal cognition.

Temporal representation and reasoning in non-human animals

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Abstract

Hoerl & McCormack argue that comparative and developmental psychology teaches us that "neither animals nor infants can think and reason about time." We argue that the authors neglect to take into account pivotal evidence from ethology that suggests that non-human animals do possess a capacity to represent and reason about time, namely, work done on Sumatran orangutans' long travel calls.

Hoerl & McCormack (H&M) argue that comparative and developmental psychology teaches us that "neither animals nor infants can think and reason about time – they rely entirely on the temporal updating system" (TA, fourth paragraph from the beginning, no section number). We disagree with this claim. We argue that certain "tasks that involve things unfolding over time" (fourth paragraph) do require temporal representational resources that the authors claim are unavailable to non-human animals. We have in mind evidence from ethology that suggests that certain non-human animals possess a capacity to represent and reason about time, for example, research on Sumatran orangutans' long travel calls (van Schaik et al. 2013; Spillmann et al. 2015). This behavior amounts to a complex action, which requires individuals to think of their lives as "temporally extended projects" (sect. 5, para. 7), and is best explained by a temporal representation and reasoning system.

Before turning to examine this evidence, we offer a few words concerning the systems invoked by H&M. First, it strikes us that the primitive temporal updating system is "temporal" in name only. It is merely a multimodal world model that gets periodically updated, by receiving new sensory inputs and by the interventions of different non-representational "timing mechanisms," which they argue "can explain how even a creature capable only of temporal updating might nevertheless display forms of behavior that are sensitive to elapsed time" (sect. 1.3, para. 6). The temporal dynamics of an animal's behavior is explained by postulating a corresponding temporal dynamic in the underlying world model. One worry we wish to raise is that, without a principled, general account of the operation of these timing mechanisms, an appeal to such a system appears ad hoc, unfalsifiable, and thereby lacks explanatory power. The purported mechanisms are made to fit the behavioral data. It is then no surprise that the temporal updating system can "explain" certain temporally sensitive behaviors.

What about the temporal reasoning system? According to H&M, this system involves genuine representations of temporal magnitudes. According to Peacocke (2017), to whom H&M, too, appeal, genuine temporal representations require "representational preservation," by which he means that the creature retains a certain conception of its environment or its own states and updates it with a "past-tense label" that relates to the amount of time that has passed. Importantly, such conception "registers certain identities" between entities represented in the past and those represented later in time. Now, why would we not think that animals have such capacity? With this in mind, we return to the evidence.

Orangutans are arboreal, semi-nomadic, and semi-solitary animals that live in dense tropical forests. Because of their environmental conditions and dispersed social structure, an ability to plan for future social and subsistence needs appears adaptive. Van Schaik et al. (2013) have examined the extent to which the direction of long calls emitted by male Sumatran orangutans (*Pongo abelii*) indicates the direction of their future travel. According to their study, the direction of spontaneous long calls emitted by male Sumatran orangutans generally predicts travel direction on the following day, and a new spontaneous long call indicates subsequent travel better than the old one would have on its own. The primary goal of these long calls appears to be to communicate to female orangutans the male's future travel direction. Finally, the range of responses to these long calls suggests that other orangutans, females as well as other males, use this information in planning their own travel and in their own communications.

According to H&M, only creatures with a temporal reasoning system can evaluate "choices that involve assessing the relative value of rewards available at different time points" (sect. 5, para. 1). If long calls indicating future travel directions can be used to indicate future states of affairs (the path traversed the following day), they must be generated by a temporal reasoning system, which would allow the animal to represent future rewards (presence of mate or foe). Long calls indicate "how things are at other times" (sect. 1.1, para. 1), that is, the animal's prospective expected location in space and time. Orangutans manifestly act according to a model of the world that exceeds what is merely experienced as present. Long calls are instances of displaced references, that is, communicative vehicles of the capacity to transmit information about something that is not present or about a past or future event (Lameira & Call 2018). Orangutan males advertise future travel direction one day in advance through long calls that facilitate associations with females. Long calls are designed to function as efficient tags of male identity across long distances in the forest, making it unlikely that males produce long calls to refer to an outside entity or event.

Therefore, contrary to the authors' suggestion, we argue that Sumatran orangutans possess the necessary representational resources for temporal reasoning. Looking back at Peacocke's criteria for temporal representation, it appears that orangutans must have a capacity to track other conspecifics across space and time, so as to coordinate their activities with the facilitation of nightly long calls. Other conspecifics appear to retain a conception of their environment that is updated with a "past-tense label" corresponding to the time since hearing the long call and "register the identity" of the emitter of the long call and the orangutan they aim to meet or avoid at a certain future time/place. This is not to say that it is impossible to posit a mechanism that does away with such temporal representations and accounts for such behavior by having the appropriate temporal dynamics. However, for the reasons mentioned above, this appears to us ad hoc and unmotivated.

On a final note, none of this is to deny that human beings have distinctive ways of representing and reasoning about time – grounded in their more intellectually demanding conceptual and linguistic skills. Rather, it is to deny H&M's claim that the latter, alone, amounts to *genuine* temporal representation, and their conception of creatures who are differently intellectually equipped as "cognitively stuck in time" (sect. 2.3, para. 3).

Updating and reasoning: Different processes, different models, different functions

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Abstract

Two issues should be addressed to refine and extend the distinction between temporal updating and reasoning advocated by Hoerl & McCormack. First, do the mental representations constructed during updating differ from those used for reasoning? Second, are updating and reasoning the only two processes relevant to temporal thinking? If not, is a dual-systems framework sensible? We address both issues below.

Hoerl & McCormack (H&M) distinguish between temporal updating and temporal reasoning as separate mental processes. The distinction is sensible and useful, and it helps synthesize many extant results in temporal cognition. Nevertheless, the authors' framework prompts two issues worth clarifying:

First, what is being updated during temporal updating?

The authors elaborate on specific constraints of the temporal updating process, but they are less clear on the mental representation that is being updated, which they refer to as a "world model." The world model they refer to bears resemblance to "perceptual mental models" described in research on event segmentation, visual perception, and mental simulation (Chua et al. 2005; Churchland et al. 1994). The distinction offered by H&M, that perceptual models and event models may be fundamentally distinct in both evolutionary and developmental terms, could help frame current theories of event cognition so long as the factors that distinguish the two are clearly delineated.

Our own recent work (Kelly 2018; Khemlani et al. 2013; 2015) can help distinguish perceptual models – which the temporal updating system produces – from event models, which are constructed during temporal reasoning. Some fundamental differences between perceptual models and event models are provided in Table 1. The table shows that both perceptual and event models are iconic, discrete simulations that represent a possible set of relations between entities. But while perceptual models come from using perceptual information to update a model of a reasoner's surroundings, event models can represent situations apart from the reasoner's ongoing experience. They can come from discourse concerning real or hypothetical scenarios that are spatiotemporally displaced; episodic memory of events in the past; and imagination about events in the future. Unlike perceptual models, event models can concern multiple situations. Consider the following description of a set of events: "The commute happened before the staff meeting. The commute happened before the conference call." The description is consistent with at least two temporal possibilities: one in which the meeting happened before the call, and one in which the call happened before the meeting. Those who fail to enumerate the different possibilities will fail to grasp the ambiguity of the description (Kelly & Khemlani 2019). Event models permit reasoners to enumerate multiple possibilities.

The table lists additional ways in which we believe perceptual models differ from event models. The differences are anticipated in part by H&M, who argue that "the temporal updating system … deals with changing input by *changing representations*, rather than by *representing change*" (sect. 1.1, para. 1). If H&M are right that temporal updating is a highly constrained cognitive process, then the representations it updates should be constrained in systematic ways that yield testable empirical predictions.

Second, is a dual-systems framework appropriate?

When theorists invoke a dual-systems account of reasoning, one fundamental assumption is that the two systems compute the same function in two different ways: an initial, rapid system computes a heuristic response based on one or more cues, and a slower, deliberative system processes the same information in a more elaborate manner (Stanovich & West 2000). The two systems rely on different algorithms to carry out the same cognitive task. But when H&M distinguish updating from reasoning, the goals of the two systems they posit differ: People update their perceptual models to maintain an accurate simulation of reality. In contrast, a person may engage in temporal reasoning to achieve many different goals, for example, planning for the future, reinterpreting the past, comprehending discourse, and understanding the sequence of a film. Because temporal updating and temporal

Table 1. (Kelly et al.) Conceptual and computational differences between the perceptual and event models

A perceptual model…	Event models…
…is an iconic, discrete mental simulation of ongoing experience	…are iconic, discrete mental simulations of temporal possibilities
…comes from perception	…come from perception, discourse, memory, or imagination
…represents a single situation	…can represent multiple situations
…is subject to attentional and working memory bottlenecks	…are subject only to a working memory bottleneck
…can't be used to infer temporal relations	…can be used to infer temporal relations

reasoning are used for different purposes, invoking the dual-systems framework may be inappropriate.

Indeed, it is not clear to us why updating and reasoning are the only processes relevant to temporal cognition. Some tasks that require the representation of time do not require reasoning at all. Consider the task of event recall (Wang & Gennari 2019). The task requires an individual to recall events that comprise some temporal interval. For example, you might summarize your previous day as follows: "I had breakfast, worked on a project, taught a class, had a meeting, then had lunch with a friend…." The task requires individuals to remember and then to represent multiple events along a mental timeline. It does not concern temporal updating and it does not require reasoning, either, because responders need not infer any novel temporal relations while recalling events in memory. The act of remembering a temporal sequence seems fundamental to temporal thinking, but the dual-systems framework that H&M espouse has no place for it.

Hence, H&M must explain whether their account allows for cognitive processes that result in mental representations of temporally ordered events, even those that do not demand explicit temporal reasoning. The "intermediate developmental stage" (sect. 3, para. 1) to which they refer presents a broad challenge to the dual-systems framework. Children may struggle to retrieve temporal sequences, not because they revert to updating, but rather because of episodic memory retrieval failures (Prabhakar & Ghetti 2019). H&M should enumerate the specific pattern of errors predicted by reverting to the updating system. Perhaps a more accommodative framework, one that retains the division outlined by H&M, should specify the different processes relevant to temporal cognition (e.g., updating, recall, reasoning) as well as the various representational and computational constraints of each process (cf. Khemlani et al. 2015).

In sum, H&M's distinction between temporal updating and reasoning is useful, so much so that it is worth refining, clarifying, and extending to address the two issues highlighted above.

The "now moment" is believed privileged because "now" is when happening is experienced

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Abstract

Hoerl & McCormack risk misleading people about the cognitive underpinnings of the belief in a privileged "now moment" because they do not explicitly acknowledge that the sense of existing in the now moment is an intrinsically temporally dynamic one. The sense of happening that is exclusive to the now moment is a better candidate for the source of belief in a privileged now.

We agree with Hoerl & McCormack (H&M) that the naïve folk conception of time is paradoxical, particularly with respect to the sense of a privileged now. However, we argue that because H&M have placed little emphasis on the subjective experience of the "now moment," they are likely to be wrong about the cognitive underpinnings of the belief in a privileged now. We doubt that the belief in a privileged now arises from an ancient cognitive system that represents the world without representing change, because the conscious experience of the now moment is inherently the experience of change.

A better model for the way humans think about time should not explain belief about temporal change primarily only with respect to thoughts about the past and future. Instead, the model should incorporate the variety of mechanisms for processing temporally dynamic stimuli that each present different kinds of temporally dynamic experience to conscious awareness in the now moment (Montemayor & Wittmann 2014; Muller & Nobre 2014). Mental time travel (Suddendorf & Corballis 2007a), which H&M rely on completely to account for the naïve human idea of time, is only one way in which humans relate to the passage of time. Yet it is arguably the least direct way we experience time because it is normally experienced only as simulation.

A more direct way we experience time is through the *flow* inherent to the sense of the present moment, which is a dynamic sense of events *happening* in the now, widely acknowledged within discussions of the phenomenology of time (Gruber et al. 2018; Prosser 2012). At any given moment, there is not only (or not at all) a subjective representation of now as a snapshot with no sense of change. There is a sense of flow; now is a single moment, but it is a moment encompassing change. The dynamic nature of the conscious sense of now is revealed in widely used phrases such as "stream of consciousness" and "what is happening now." Readers unfamiliar with the phenomenological literature are invited to engage in introspection about their experience of existing in the current moment. Even in a stimulus-poor environment, our experiences in the now moment are dynamic, including breathing, or chains of thoughts. Perceptions in the now are frequently of momentary dynamic events: a flash of light, a spoken word, a looming object. Many conscious perceptions are meaningless outside the context of temporal dynamics. For example, the sense of looming and other motion perceptions inherently relate to change (Gibson 2014), and sound is inherently a temporal phenomenon.

Besides the phenomenological or introspective analysis, various objective observations indicate that the now moment encompasses happening events rather than just a millisecond snapshot. For example, multiple events occurring within a time window (up to 300 ms depending on modality and number of events) can be discriminated even though their order cannot be determined (Montemayor & Wittmann 2014), indicating that they were experienced as separate happenings within one moment. Further evidence, for example, from language perception, indicates that there are different kinds of experience of now, with different aspects of dynamism (Poeppel 2003; Wittmann 2011). The "simultaneous now" is suggested to last approximately 250 ms (still long enough to contain events), whereas the "conscious now" lasts approximately 3 seconds (Montemayor & Wittmann 2014).

Further evidence for the sense of events happening now comes from work on visual perception. Suitably arranged dynamic stimuli together give rise to our sense of causality in the here and now (Scholl & Tremoulet 2000). In the same way that changes to the dynamic character of the stimuli can abolish the sense of causality, disruptions to the temporal sequence can also remove the sense of happening that is a cornerstone of the subjective sense of temporal flow (Gruber & Block 2013).

There are numerous functional reasons why the experience of the now moment must be more than a millisecond snapshot. Our perceptions are integrated with our actions (Pezzulo & Cisek 2016), with the consequence that our perception of the now moment is one of the dynamic affordances currently offered. To perform even the simplest goal-directed actions, short-term temporal dynamics are taken into account (Gibson 2014).

Interestingly, there is evidence that on the lowest levels of subconscious perception, stimulus representations are in fact not dynamic, and perception rather takes the form of a series of discrete static representations. This is even held to be plausible for auditory stimuli although sound is inherently temporally dynamic (VanRullen et al. 2014). The dynamic perceptions reaching our awareness are therefore not necessarily veridical in the sense of arising directly from the true dynamism of real events. Rather, this is likely to represent a reconstruction (Gruber et al. 2018). However, the only thing that matters for our current argument is that the lowest levels of perception subject to conscious awareness usually constitute dynamic representations.

We agree with H&M that there is little evidence for mental time travel in most non-human animal species or in human infants. However, given the different ways of experiencing time, it is arguably inappropriate to dichotomize organisms according to "whether or not [their] model of the world contains a temporal dimension" (sect. 1.3, para. 4). Rather than the lack of evidence of mental time travel implying that such organisms have no representation of temporal change, it implies they may have no representation of change except for the change happening in the current moment. In other words, their representational timeline may be very short.

Given the dynamism of the experience of now, our counterproposal for what makes now special in naïve human belief is that *now is the only time when events are experienced to happen.* Of course, events are also believed to have happened in the past and are expected to occur in the future, but mental time travel typically involves simulation rather than experience of those events. We argue that our account is more parsimonious than H&M's because their model implies a curious and unsupported phenomenon: that people ignore their salient experience that things happen in the now moment when they are thinking about what now actually is.

Let's call a memory a memory, but what kind?

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Abstract

Hoerl & McCormack argue that animals cannot represent past situations and subsume animals' memory-like representations within a model of the world. I suggest calling these memory-like representations as what they are without beating around the bush. I refer to them as event memories and explain how they are different from episodic memory and how they can guide action in animal cognition.

In the target article, Hoerl & McCormack (H&M) propose a dual-systems account for temporal cognition and argue that non-human animals can only use the temporal updating system whereas humans utilize the temporal reasoning system as well. I am sympathetic to dual-systems approaches in general, but it seems that H&M try to explain too much with too little in animal cognition.

In H&M's view, the model of the current world does all the heavy lifting in animal cognition. The model represents how things are in the current environment; contains information about objects, their features, and locations including goal states; supports single-trial and sequential learning; and can be updated as things change in the environment. Yet this notion of a model is left unpacked. If the model is just for the present state of the world, why not use the world as its own model? Is the model just a cognitive map or a full-blown replica of the world? What is the format in which the information is stored? Is it perceptual or propositional or something else? Is the model constructed componentially? If so, what binds different kinds of representations into a single unit? If not, how could the model be updated so swiftly? Without answers to these kinds of questions it is difficult to assess whether non-human animals operate with a model or not.

Arguably, any attempt to specify what a model of the current world consists of has to include perceptual elements that go beyond an animal's immediate sensory range. H&M seem to agree with this, as they accept that non-human animals can continue to represent an object that they no longer perceive as part of their current environment. These memory-like representations are obtained from the animals' past experiences and are presumably retained insofar as they are useful for the organism. H&M want to subsume these memory-like representations within an animal's model of the world, but it is possible to be more precise here.

In earlier work (Keven 2016; 2018), I called these types of representations event memories and argued that we can understand the mnemonic abilities of non-human animals (and young children) with event memory without ascribing them a capacity for full-blown episodic memory. According to the dual-systems thesis that I proposed, event memory is a snapshot-like memory system predominantly in the form of visual images, whereas episodic memory requires additional higher-order *inferential processes*. The episodic memory system takes event memories as inputs and binds them into a whole by linking multiple events into a temporal sequence, establishing casual relations between temporally separated events and arranging events in a converging structure such that multiple events are bound together to enable an outcome. Unlike episodic memory, temporal, causal, and teleological relationships between events are not specified in event memory. Event memories are fleeting and fragmentary in this sense as they are not bound into a stable whole. Hence, event memories are retained as long as they are relevant for current tasks, otherwise they are rapidly forgotten.

H&M claim that such free-floating representations cannot systematically guide action. Although event memories are not bound into a stable whole, they are still tied to the current goals of the organism and can be activated by task-based cues from working memory. In this respect, event memories differ from Redshaw's (2014) uncontextualized representations, as the goals of the organism actually relate event memories to the current context. This is a different kind of contextualizing than what Redshaw seems to have in mind, as it still does not require meta-representational abilities. Instead, the current goals of the organism activate relevant representations that are associated with achieving that goal (Hommel 2009; Hommel et al. 2001). The idea is that when an organism is engaged in a task, task-relevant representations, such as recent events, locations, and other relevant perceptual or semantic information, are activated. If the task is time sensitive, this process could also incorporate temporal information from an interval timer mechanism similar to what H&M envisions. These activated representations can then guide the selection of actions according to their expected outcomes.

To illustrate how this process might work, consider Clayton and Dickinson's (1998) original study that H&M discuss. Event memory can assist scrub jays by keeping track of caching events (i.e., what did the bird cache where). Because the recovery task is time sensitive, the birds could also use an interval timer mechanism to control how long these event memories would remain task relevant. During the training phase of the study, scrub jays seem to learn that worm-caching events are relevant for the recovery task only for a short time period and there is no need to retain them for longer. In 124-hour trials, then, the birds could actually be operating with only the event memory of caching peanuts, and hence they search for peanuts. In 4-hour trials, however, because the elapsed time is short, event memories for caching peanuts and caching worms would both still be active. In this case, the birds search for worms as their preferred food.

It is important to note that none of these processes require remembering the actual experience of caching the food items, unlike an interpretation based on mental time travel (Salwiczek et al. 2010). The birds could remember in the same way I can remember where my keys are without remembering the actual experience of where I put them (Malanowski 2016; Suddendorf & Busby 2003). Event memory is based on automatic perceptual processes and does not require conscious attention at encoding or retrieval.

To conclude, animals need to keep track of what has happened to effectively deal with day-to-day tasks that are extended over time. Event memory can guide animals by providing a record of progress in such tasks.

Thinking about time and number: An application of the dual-systems approach to numerical cognition

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Abstract

Based on the notion that time, space, and number are part of a generalized magnitude system, we assume that the dual-systems approach to temporal cognition also applies to numerical cognition. Referring to theoretical models of the development of numerical concepts, we propose that children's early skills in processing numbers can be described analogously to temporal updating and temporal reasoning.

Hoerl & McCormack (H&M) describe two systems that supposedly differ in the processing of temporal information and the underlying representation of time. We endorse this notion and propose that the dual-systems approach is not restricted to the dimension of time. The basic assumption is that time, as well as space and number, is part of a generalized magnitude system (Walsh 2003). Therefore, if we adopt the view of a generalized system for magnitude processing and, at the same time, accept the proposed dual-systems approach to account for the domain of temporal cognition, then the two systems should also apply to other domains of magnitude processing. In the following, we give examples of processes in numerical cognition that might correspond to those processes that H&M ascribe to the temporal updating system, an intermediate phase, and the temporal reasoning system.

The development of basic and advanced numerical knowledge in humans is assumed to rely on an evolutionarily ancient innate system dedicated to extracting and representing approximate numerical magnitude information (Amalric & Dehaene 2016; Feigenson et al. 2004; Piazza 2010; Starr et al. 2013). Recent meta-analyses support this view by showing a significant association between approximate numerical magnitude processing skills and symbolic math performance (Chen & Li 2014; Fazio et al. 2014; Schneider et al. 2017). We suggest that sensitivity for approximate number might be interpreted analogously to the elapsed-time sensitivity in temporal cognition, which has been described as a mechanism of the temporal updating system. According to theoretical models on the development of numerical concepts, children learn the counting sequence by rote before they understand the numerical meaning of number words (Fuson 1988; Krajewski & Schneider 2009a; 2009b). Consistently, empirical evidence suggests that children are able to recite the counting sequence before they know the exact cardinal meanings of all numerals in that sequence (Le Corre et al. 2006). In our opinion, children's early ability to recite the counting sequence is similar to their sensitivity for recurring event sequences. By analogy with mechanisms that H&M ascribe to the more primitive updating system in the temporal domain, we suggest that both the processing of approximate numerical magnitudes and the ability to reproduce the counting sequence do not necessarily involve a mature and flexible concept of number.

At a further stage of numerical development, children assumingly become aware that number words are linked to quantities. Children at this stage rightly decide which of two number words (e.g., "five" vs. "three") represents more or less, possibly without being able to represent the exact difference between these numbers (Krajewski & Schneider 2009a; 2009b). This might be analogous to what H&M have described as an intermediate phase for the temporal domain; young children discriminate past and future points in time relative to the present without having access to the specific temporal relations between them.

The insight that differences between numbers also consist in numbers is seen as an important step toward complex reasoning about numerical magnitudes (Fuson 1988; Krajewski & Schneider 2009a; 2009b). It enables children to work with specific distances between numbers, which corresponds to the key characteristic of temporal reasoning as proposed by H&M. They suggest that temporal reasoning operates on the basis of a temporal concept that includes unique addresses for different points in time as well as the temporal-causal relations between these points. Furthermore, they argue that temporal reasoning relies on a spatial representation of time in the form of a timeline. Similarly, numerical reasoning is assumed to rely on the flexible manipulation of numerical magnitudes on a mental number line (Dehaene 1992; Siegler & Braithwaite 2017). Apparently, flexible reasoning about both temporal events and numerical magnitudes requires a concept of the underlying principle that allows any event (or number) to be logically related to another.

From our point of view, the outlined similarities in children's processing of time and number endorse the application of the proposed dual-systems approach to numerical cognition. It has to be noted, though, that the theoretical models of numerical development cited above assume fine-grained competence levels that build upon each other. In contrast, the dual-systems approach distinguishes only two cognitive systems. However, H&M also acknowledge that premature forms of the temporal reasoning system exist, which they describe as part of an intermediate phase in development. Further specification of the proposed two systems and their associated mechanisms is needed to understand their interplay and possible transitional stages throughout development. Our proposition that H&M's approach might apply to other dimensions of magnitude processing certainly requires validation by future investigations. In our view, systematic comparisons of children's competencies across dimensions and across development will provide a valuable contribution to the debate about the nature of the cognitive system, or the systems, required for the processing of magnitude information.

Thinking about the past as the past for the past's sake: Why did temporal reasoning evolve?

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Abstract

Hoerl & McCormack discuss the benefits of temporal reasoning mainly with respect to future planning and decision making. I point out that, for humans, the ability to represent particular past times has distinct benefits, which are independent from contributing to future-directed cognition. Hence, the evolution of the temporal reasoning system was not necessarily driven primarily by its benefits for future-directed cognition.

Hoerl & McCormack (H&M) present a compelling distinction between different cognitive systems for dealing with temporal information. It is commonly assumed that the evolution of temporal reasoning, as H&M describe it, must have been driven by the benefits representing different times brings for planning and decision-making (Boyer 2008; Schacter & Addis 2007; Suddendorf & Corballis 2007a). Similarly, H&M discuss the benefits of temporal reasoning mainly in regard to its effects for temporal discounting in decision-making. Focusing on the purely future-directed benefits of temporal reasoning does not by itself, however, explain why we should expect this capacity to be human specific. Arguably, other animals would equally benefit from improvements to planning and decision-making through temporal reasoning.

By contrast, as H&M also point out, for other animals, "opportunities to benefit from knowing that a situation of a particular kind obtained at a unique time in the past are relatively rare, because that time itself will never come around again" (sect. 6, para. 2). For humans, however, the past seems to have a special status independent from what it tells us about the future. This fact becomes particularly apparent in conversational behavior where people have been found to display a "retrospective bias" by talking two to three times more often about the past than the future (Demiray et al. 2018). Some consequences of the ability to represent time should have generated evolutionary pressure for the ability to represent the past in its own right, independently from its benefits for future-directed cognition.

Most prominently, those benefits exist in the domain of causal thinking, specifically in the ability to represent token cause-and-effect relationships ("Mark died because he was shot") as opposed to type causal relationships ("Being shot kills people") (Campbell 1996). We can distinguish physical, psychological, and social cause-and-effect relations.

Regarding the physical domain, being able to represent the history of environmental states to draw inferences about token cause-effect relationships benefits primarily inductive learning. Inferring the cause of a physical state allows one to build causal maps of type causal relations, which are in turn important for future-directed decision-making. As such, here, particular past events are important primarily insofar as they inform inferences to type causal relations.

Therefore, in the physical domain, the ability to represent token past events can indeed be expected to be beneficial, insofar as it supports future-directed cognition. As H&M point out, however, inductive learning arguably functions more effectively not by recourse to retrospective representation of particulars, but through use of "a general learning system geared toward encoding and retaining information about regular, stable, or recurring features of the environment" (sect. 6, para. 2). By contrast, in the psychological and social domains, representing particular past events has benefits in which the particularity and pastness of events matter for their own sake.

First, the ability to represent particular past events allows one to represent the causal history of mental states. In essence, representing the token cause of a mental state is to represent the source of this state. The benefits of the ability to represent source information are particularly apparent in the case of beliefs (Cosmides & Tooby 2000; Mahr & Csibra 2018). Representing the causes of one's own and others' beliefs allows one to gauge their reliability and the conditions under which they should be revised (Király et al. 2018). Moreover, this ability facilitates the transmission of beliefs because the causal history of a belief can be given as a reason for why it should be accepted (as, e.g., in the case of beliefs acquired through firsthand experience).

Second, in contrast to physical cause-effect relationships, knowing the cause of a specific token effect in the social domain has benefits not (primarily) because it allows one to draw inductive inferences about type causal relations but because it can serve to establish the existence of this social effect in the first place (Mahr & Csibra, in press). If Bob takes money out of my wallet while I am distracted, it follows that he stole from me. While many other things can be inferred from this event, too (that there was money in my wallet, that Bob has quick fingers, etc.), knowing what occurred in this specific circumstance primarily has importance insofar as it establishes specific obligations and entitlements. As such, token events have significance in the social domain in virtue of their particularity.

In fact, in many circumstances, events have lasting social consequences without also leaving physical traces behind, which could prove the occurrence of the event in the first place. If I promise to meet you at 5 p.m. tomorrow at the train station, nothing but your memory of the fact that I indeed made such a promise will serve to hold me accountable after the fact. In such cases, mental representations of particular past events are crucial to establish the existence of the social effects of these events. After all, usually such effects (e.g., my commitment of meeting you tomorrow at 5 p.m.) only exist insofar as they are mentally represented by the parties involved. To a large extent, the fact that our lives are heavily determined by social norms governing the social cause-and-effect relationships of events unfolding around us explains why we seem to care so much about what occurred in the past.

In sum, for humans there are distinctive benefits of representing the past not connected to future-directed cognition and decision-making. As such, we should expect the operation of selection pressures on the ability to represent past times, which might not have operated over the ability to represent the future. While, if H&M are right, the development of the temporal reasoning system should result in the ability to think about both the past and the future, it is by no means obvious that the evolution of this system was solely, or even primarily, driven by its benefits for future-directed cognition.

From temporal updating to temporal reasoning: Developments in young children's temporal representations

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Abstract

Evidence from our research on young children's temporal understanding supports Hoerl & McCormack's view that young children rely on a temporal updating system to change representations over time. We propose that the shift from temporal updating to temporal reasoning is enabled by children's expanding representations of event sequences, along with developments in language, memory, and other cognitive competencies.

In Hoerl & McCormack's (H&M's) dual-systems approach, infants and very young children rely on a temporal updating system to change representations over time, but older children develop a more mature temporal reasoning system that allows for representation of change. Although this developmental account is consistent with findings from our research on children's temporal understanding, H&M do not explain the processes leading to this shift.

Evidence for young children's use of a temporal updating system comes from our research indicating that young children are consistently better at forward temporal thinking than backward temporal thinking. We tested 3- to 5-year-olds' understanding of *yesterday* and *tomorrow* with a picture-selection task in which children heard sentences such as, "I carved the pumpkin yesterday," and were asked, "What does it look like now?" (Zhang & Hudson 2018a). Answering this question involves thinking forward from yesterday to today. However, children could also respond correctly by simply updating their representation of the pumpkin from an intact pumpkin to a carved pumpkin without considering the temporal relationship between yesterday and today. In contrast, children were less accurate when backward thinking was required, as when they heard the sentence, "I'm gonna carve the pumpkin tomorrow," and were asked, "What does it look like now?" To answer this question correctly, children needed to represent the change as occurring at a future time point and temporally de-center between the future point and the present; this requires a temporal reasoning system. Hence, children could rely on a temporal updating system to solve forward reasoning problems, but not backward reasoning problems.

Superior performance in forward thinking was observed across several temporal understanding tasks: In English-speaking and Mandarin-speaking children (Zhang & Hudson 2018b); in tasks involving change in possession as well as change in physical states

(Zhang 2019); and in a simpler task in which children were asked questions such as, "What did the pumpkin look like before I carved it?" or "What will the pumpkin look like after I carve it?" (Zhang & Hudson 2018a). Tasks using spatial cues to test children's understanding of the sequential relations between time points such as yesterday, today, and tomorrow also elicited more errors in backward problem solving (Zhang 2019). These findings support the view that young children can solve problems that involve temporal updating before they are capable of temporal reasoning.

This shift from temporal updating to temporal reasoning is a critical developmental achievement. However, it is unclear what happens early in development that prepares children for the ability to reason about time at 4 to 5 years of age. We propose that development proceeds from representing change as ordinal updates (i.e., "and then, and then, and then"), to ordinal representation in the form of before-after relations between units within events, to interval measurement with event-independent measurement units (e.g., days), to the ratio measurement involved in the clock and calendar systems.

The mature adult conception of "common time" is linear, unidirectional, event independent, and unified; it is a common conception among humans and is common to all changes (McCormack & Hoerl 2017). Children's awareness of before-and-after states of change is the beginning of their construction of common time. When children grasp the relationship between an initially intact block tower and a fallen block tower as before and after (without necessarily using the linguistic expressions "before" and "after"), they engage in ordinal representation. They then expand the scope of the units considered in this relation: from states (e.g., toothbrush on counter-toothbrush in hand), to actions or events (e.g., bathing-teeth brushing) to event sequences (e.g., bedtime routine).

Expanding the scope of the ordered units from actions within events to events within a day is difficult because there is variability in daily event chains. For example, on some days, there is a car ride to preschool following the morning routine of getting up, dressing, and having breakfast, but on other days, this car ride does not follow. When children notice the recurring pattern of event sequences in a day, they can chunk the "day" as a unit, and place days in a before-and-after relationship. The day is a universal unit of change, easily observable by the astronomical light-dark cycle and demarcated for children by going to bed and getting up. This is still ordinal representation. The relationship between yesterday, today, and tomorrow is an ordinal one. However, once the ordered unit has reached the event-independent "day," using this unit for interval measurement is not a big leap, for example, "two days." The grasp of the unit "day" is a prerequisite for understanding the week and the other units of the calendar system. It is the repetition of temporal measurement units that gives a cyclical aspect to linear common time.

In our research with 3- to 6-year-olds, we found that irrespective of age, children with richer scripts for event sequences in the day were better at ordering pictures of events in the day, naming the parts of the day, naming the days of the week, and naming the day before Wednesday. Better receptive vocabulary and pattern reasoning ability were also related to more extensive scripts (Mayhew & Hudson 2017; Mayhew 2018).

These findings not only offer evidence for the connection between elaborate representations of event sequences in the day and the ability to consider the day as a unit, but also point to the importance of other cognitive skills in the development of temporal reasoning. Memory skills are necessary for chunking the day as a unit; numeracy skills are needed for interval measurement of duration; pattern reasoning skills facilitate observation of recurrent event sequences; and language skills are needed to map words to observed temporal relationships.

In our view, the temporal updating system, with its sensitivity for ordered sequences, bootstraps the temporal reasoning system by furnishing the "and then, and then, and then" sequences where before-and-after relations can be noticed. Children's expanding event representations, along with developments in language and other cognitive competencies, provide the foundation for reasoning about temporal sequence. It is these developments that enable the shift from the temporal updating system to the temporal reasoning system.

Problems with the dual-systems approach to temporal cognition

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Abstract

Contrary to Hoerl & McCormack (H&M), we argue that the best account of temporal cognition in humans is one in which a single system becomes capable of representing time. We suggest that H&M's own evidence for dual systems of temporal cognition – simultaneous contradictory beliefs – does not recommend dual systems, and that the single system approach is more plausible.

Hoerl & McCormack (H&M) propose that humans develop two systems for representing the world: one that possesses a temporal dimension (and therefore can be used to reason about time) and one that lacks a temporal dimension (and therefore cannot be used to reason about time). Although H&M's proposal is one of many to posit two systems of human cognition (i.e. dual-systems theories) (Evans 2008; Melnikoff & Bargh 2018), it is nonetheless highly original. To our knowledge, it is the first dual-systems theory to define its systems in terms of possessing versus lacking a single representational dimension. Most other dual-systems theories define their systems in terms of neural substrates (e.g., neocortex vs. hippocampus), modes of processing (e.g., associative vs. propositional), and/or operating characteristics (e.g., automatic vs. controlled). Although we appreciate H&M's innovation, we are skeptical about their dual-systems approach to temporal cognition. A preferable approach, we will argue, would be to posit that the ability to reason about time emerges from the temporal enrichment of a single system (Keren & Schul 2009; Kruglanski & Gigerenzer 2011; Osman 2004).

H&M's evidence for dual systems is that people simultaneously affirm two contradictory beliefs about time: (i) only the present exists, and (ii) the past, present, and future all exist equally. H&M assume that a single system cannot affirm contradictory beliefs simultaneously, and therefore conclude that people's beliefs about time are affirmed by multiple systems. This type of argument was pioneered by Sloman (1996), whom H&M follow by never explaining precisely why a single system cannot simultaneously affirm contradictory beliefs. What is the problem supposed to be? Presumably, a single system can operate according to the rules: "If condition x is satisfied then affirm the belief p" and "If condition y is satisfied then affirm the belief *not-p*," where x and y are not mutually exclusive. If x and y were satisfied simultaneously, would such a system not simultaneously affirm p and *not-p*? We submit that it would, and hence, simultaneous contradictory beliefs do not recommend dual systems (Bermúdez 2000; Betsch & Fiedler 1999; Ferguson et al. 2014; Gigerenzer & Regier 1996).

Let us be more concrete. Suppose that a system determines whether things exist using two rules: the *present rule* and the *causality rule*. The present rule states that only temporally present things exist. The causality rule states that things exist if and only if they can affect or be affected by temporally present things. Both rules seem plausible enough. A common-sense list of things that exist might include Oprah Winfrey, Stonehenge, and salami (all present things that can affect or be affected by present things) but would not include Sherlock Holmes, Shakespeare's original Globe Theatre, or Martian outposts (all non-present things that cannot affect or be affected by present things). Notice, however, that the two rules disagree about the existence of the past, present, and future. The present rule entails that the present is all that exists. Yet the causality rule entails that the past, present, and future all exist equally (because the past affects the present and the present affects the future). Therefore, the simultaneous application of the present rule and the causality rule by a single system would produce the simultaneous contradictory beliefs that motivated H&M's dual-process approach in the first place.

One might question our line of reasoning by arguing that the human mind cannot affirm the *conjunction* of two contradictory beliefs (i.e., a single belief of the form *p & not-p*). Indeed, it is hard to imagine someone genuinely affirming the conjunctive belief that *only the present exists and the past, present, and future all exist equally.* But nothing like this needs to occur when a single system simultaneously affirms contradictory beliefs. The simultaneous affirmation of contradictory beliefs does not entail the affirmation of the conjunction of those beliefs (Bermúdez 2000). The statements "S believes p at time t" and "S believes *not-p* at time t" do not jointly entail that the S ever has a single belief of the form *p & not-p*. Accordingly, a human mind that is incapable of affirming conjunctions of contradictory beliefs can still (within a single system) affirm contradictory beliefs simultaneously. We doubt, therefore, that the simultaneous holding of contradictory beliefs requires dual systems.

Having refuted H&M's evidence for their dual-systems theory, we hold in favor of the alternative hypothesis that temporal reasoning abilities emerge from the temporal enrichment of a single system. We suggest that this alternative hypothesis requires fewer assumptions and auxiliary mechanisms than H&M's dual-systems approach, and therefore is (necessarily) less likely to be wrong. The problem is that an agent with both a temporal reasoning system (i.e. a temporally enriched mental model) and a temporal updating system (i.e., a temporally impoverished mental model) has two systems with which to reason about all non-temporal dimensions. Such an agent could use either system to reason about distance, for example, because distance is represented in both systems. This raises a number of questions. Which system would such an agent use to compute its shortest route home, and what would determine this? If the agent used one system to compute its shortest route home, would the other system have access to the answer? If so, how would information transfer between the two systems? To be able to answer these questions H&M must specify how the systems are selected for processing non-temporal information, and how non-temporal information transfers between the two systems, if at all. Doing so will require H&M to make additional assumptions and to posit additional mechanisms, all of which have the possibility of being false, necessarily rendering the dual-systems theory less plausible than the alternative hypothesis that temporal reasoning abilities emerge from the temporal enrichment of a single system.

On believing that time does not flow, but thinking that it seems to

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Abstract

Hoerl & McCormack (H&M) posit two systems – the temporal updating system and the temporal reasoning system – and suggest that they explain an inherent contradiction in people's naïve theory of time. We suggest there is no contradiction. Something does, however, require explanation: the tension between certain *sophisticated* beliefs about time, and certain phenomenological states or beliefs about those phenomenological states. The temporal updating mechanism posited by H&M may contribute to this tension.

Hoerl & McCormack (H&M) contend that a contradiction in people's naïve theory of time (Callender 2017), which represents the movement of the now both as being an objective matter, independent of perspective, *and* as being a purely subjective matter, dependent on temporal perspective, can be traced to two mechanisms they posit: the temporal updating and temporal reasoning system Specifically, H&M suppose people believe both that only a single time is objectively now and that whatever time one is at, *that* time is now. H&M propose that the belief in the subjectivity of the now is enabled by our temporal reasoning system, and the contradictory belief in the objectivity of the now originates in the temporal updating system that we share with animals.

Very likely, people do believe that there is an objective moving now and simultaneously think that whatever time they are at, that time is now. However, unlike H&M, we do not think that this means they have an inconsistent representation of the world, as containing a now that is both objective and essentially perspectival. For if, as many have supposed, our naïve representation of time is one in which only one moment exists – the present – then that moment is both objectively now, and whichever moment one is located at, *that* moment is now (because there is only one moment at which to be located). This kind of naïve representation does not involve any inconsistent beliefs about the nature of the now.

We do think that there is a tension between the perspectival view of the now and aspects of mental life. H&M point out that "even Einstein … continued to be troubled by what he called the 'problem of the Now'" (Carnap 1963, cited in the H&M, sect. 4, para. 10). But it is unlikely that Einstein held the contradictory beliefs relied on by H&M – that the now's location and movement are both an objective and subjective matter. Instead, we think that after Einstein acquired a *sophisticated belief* that there is no objectively moving now, in some sense it still *seemed* to him as though there was an objectively moving now. But this seeming may be different from a belief that there is an objectively moving now.

What is the source of the seeming that the now moves or the inclination to think that it seems to? A common approach is to suppose that there is a phenomenological seeming – an illusion – as of the now moving (Callender 2008; Dainton 2011, p. 405; Hohwy et al. 2015; Ismael 2012; Le Poidevin 2007; Prosser 2012). Such an approach has an advantage over the view that the seeming is just a belief state, for we know that illusory phenomenal states can be difficult (or impossible) to eliminate even in the face of explicit beliefs that they are illusory, unlike beliefs themselves: typically, a belief that P is not difficult to eliminate when one comes to believe not P.

Therefore, the temporal updating system, or something like it (Prosser 2006; Hartle 2005), may generate *phenomenology* as of the now moving, which is resistant to change even in light of a more sophisticated empirically informed belief that the now does not move (a belief that may be possible only because of something like H&M's other system, the temporal reasoning system). In this view, this phenomenology is resistant to change even when one comes to believe that the now does not move because it is generated by a primitive system that is, at least in part, informationally encapsulated. Its output – the phenomenology as of a moving now – is not altered by explicit beliefs generated by other, higher-level systems. Hence, even when people come to believe that the now does not move, it still seems to them as though it does. In this view, when we say that it seems as though the now moves, this is because we are suffering from a phenomenal illusion. A number of aspects of experience have been highlighted in attempts to explain this illusion, such as our motion phenomenology (Ismael 2012; Le Poidevin 2007, p. 76; Paul 2010), our phenomenology of change (Paul 2010, p. 346), and now H&M's temporal updating system. We think it noteworthy that H&M's updating system bears some similarities to the system posted by Hohwy et al. (2015), in the service of explaining why we suffer a phenomenal illusion as of a moving now. However, to us these accounts leave something to be desired, in that it is not clear exactly how motion, change, or other aspects of phenomenology might yield the phenomenology as of a moving now.

Recently it has been suggested that there is not a phenomenal seeming as of the now moving: instead, there is simply a *belief* that there is such a phenomenological seeming (Bardon 2013, p. 95; Braddon-Mitchell 2013; Deng 2017; Hoerl 2014a; Miller et al. 2018.) In this view, people have a false belief about the content of their phenomenal states. Change phenomenology, and the temporal updating system posited by H&M, may contribute to a feeling that the now moves, but there may be no specific phenomenological content as of a moving now. Instead, people mistakenly *believe* that their phenomenology is as of a moving now. Miller et al. (2018) discuss a few possibilities for how people may have ended up with false beliefs about their phenomenology. One such possibility is that multiple factors lead us to misdescribe our phenomenology using language of a moving now, and that generates in us the belief that the world seems to contain a moving now. Conceivably, H&M's temporal updating mechanism may generate a phenomenology that could be mistakenly described as a phenomenology of a moving now.

On the human uniqueness of the temporal reasoning system

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Abstract

A central claim by Hoerl & McCormack is that the temporal reasoning system is uniquely human. But why exactly? This commentary evaluates two possible options to justify the thesis that temporal reasoning is uniquely human, one based on considerations regarding agency and the other based on language. The commentary raises problems for both of these options.

A central claim by Hoerl & McCormack (H&M) is that humans are endowed with a "temporal reasoning system" unique to them, whereas animals are guided only by a "temporal updating system," which is "both phylogenetically and ontogenetically more primitive" (introduction, paras. 2 and 3). This commitment informs their interpretation of influential findings on the cognitive capacities of scrub jays. Originally, these were considered as evidence that jays have the capacity for reasoning, or drawing inferences about time, including abilities for mental "time travel" (Clayton & Dickinson 1998). The authors reject this interpretation. Their dual-systems model proposes that all animals operate only on the basis of a temporal updating system, which effectively makes the temporal reasoning system a uniquely human capacity. But what exactly is uniquely human about the temporal reasoning system?

H&M's dual-systems perspective on temporal cognition provides a persuasive and comprehensive framework that is well supported by the empirical evidence. Their specific commitment to human uniqueness, however, may prove problematic. The options to support this claim are limited in light of the numerous and wide ranging findings that have gone a long way toward disproving the uniqueness of capacities long held to be uniquely human (most recently, de Waal 2016).

The authors explain their dual perspective in terms of Kahneman's (2011) systems 1 and 2, which distinguish two general modes of inferential reasoning, a fast and frugal one and a slow and effortful one. Independent argumentation is needed to demonstrate that these cannot be present in some animals. Moreover, Kahneman's two systems concern rational decision-making, rather than the representation of navigational magnitudes, such as time. Crucially, neither of these issues settles the controversy regarding human uniqueness with regard to the temporal reasoning system. Therefore, it seems that one needs a better reason than a general appeal to systems 1 and 2 to conclude that all animals are entirely incapable of representing time as such.

The temporal reasoning system affords, according to H&M, the ability to reason about and represent time itself. Given their reliance on Kahneman's work, they appear to assume that such reasoning is inferential. As they argue, the temporal updating system represents change, and is updated in the present moment through a maplike structure. Animals are "stuck in time" because they cannot think of other times at all – their minds cannot meander through time; only their present-bound map can be used to update temporal features. Yet maps certainly can be used to draw inferences. For example, my indexical location (I am here now) is updated not only with respect to the here but also with respect to the now. An animal with minimal temporal capacities will be able to infer that not everything happens simultaneously in the now, that some durations are longer than others, and that change is essentially related to time. So, it seems, animals would be capable of representing time as such by representing simultaneity, duration, and time order. Moreover, these representations support inferential reasoning, albeit of an implicit or Helmholtzian kind (e.g., if this lasts a bit longer, I shall switch to the shorter task). Therefore, perhaps the distinction between temporal reasoning and updating should not be drawn in terms of inferential capacities. In any case, a central issue to properly interpret their dual-systems model is whether an animal really can adjust its maps and representations of the world at any point in time without essentially relying on representations of time *as such*.

But let us grant that temporal reasoning is unique to humans. Why exactly is it uniquely human? There seem to be two plausible options here. One option is that the autonoetic function of episodic memory (Tulving 1972) is what makes temporal reasoning uniquely human (for a dual-systems account of time cognition that endorses this type of agency approach without the commitment to human uniqueness, see Montemayor 2017). This interpretation of temporal reasoning, however, would deny animals a sense of agency that seems necessary for basic decision-making, which has been documented across species (for a more flexible approach that attributes "event memories" to animals without assigning episodic memories to them, see Keven 2016). More precisely, H&M's approach would deny animals time-representation capacities based on an autonoetic and anthropocentric constraint that may not be necessary for the proper functioning of temporal reasoning.

An alternative option is language. This might be the best option because the justification for human uniqueness is not based on some type of introspective autonoesis imposed on temporal cognition. Rather, human uniqueness would be based on the representational *format* of the uniquely human temporal reasoning system. The authors seem to favor this view. They assert that the use of tense appears very early in infancy and that it is plausible that language is necessary for the development of the temporal reasoning system (introduction, para. 2; sect. 3.2, para. 7). If language is what makes temporal reasoning uniquely human, then we have a possible explanation of the gap between us and other species. But if this is the explanation, then much more needs to be said about the implications of language for the authors' dual model. Perhaps the influence of language is to reformat all of temporal perception through syntactic tree-like patterns, which manifests in what Fitch (2014) has called "dendrophilia." This account would assume, however, the view that language is a uniquely human capacity, an approach that is not entirely uncontroversial.

It is also unclear what kind of influence language *might* have on time cognition in humans, or how the reasoning system affects the updating system through linguistic representations. Types of "time traveling" through inference in humans might be compatible with similar capacities in non-human species—a view in which time traveling is not determined by language. Issues concerning the scope of linguistic influences need to be addressed more explicitly. There might be other alternatives to justify the human uniqueness of temporal reasoning, but H&M must present and justify them explicitly as part of their model to provide a more complete understanding of their interesting proposal.

A dual-systems perspective on temporal cognition: Implications for the role of emotion

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Abstract

This commentary explores how emotion fits in the dual-systems model of temporal cognition proposed by Hoerl & McCormack. The updating system would be affected by emotion via the attentional/arousal effect according to the attentional gate model. The reasoning system would be disrupted by emotion, especially for traumatic events. Time discrepancies described in the dual-systems model are also explained.

Hoerl & McCormack's (H&M's) model of temporal cognition is based on two parallel systems: (1) a primary system available to any sentient creature (i.e., the updating system) and (2) a cognitive-based system available only to humans (the reasoning system). Furthermore, according to the model, the reasoning system would be accessible only to children from about the age of 3 years, although this access would remain partial until the age of about 5 years. However, the model did not mention the potential implication of emotion in either of these systems. Therefore, we try to broach how emotion could affect these two systems separately among humans (because the literature on the emotional interference in time perception is scarce among animal studies).

According to the model, the updating system would include a simple timer accessible to any creature, allowing them to measure duration between two events, or to monitor time passing by after a specific event. This timer appears to fit the timing mechanism – the scalar expectancy model – proposed by Gibbon et al. (1984), which was first validated among animals, and further supports the validity of this timer mechanism in the model. According to this timer model, a pacemaker-like mechanism emits pulses, which are recorded in an accumulator, the emission starting at the beginning of an interval and finishing at the end of it. The accumulated pulses are then compared to previously stored pulses, facilitating decision-making. Interestingly, a modification of this model, the attentional gate model (AGM) (Zakay 2000) accounts for the emotional interference. According to the AGM, two potential processes would be at stake in the presence of emotional stimuli: an attentional effect and an arousal effect. The attentional effect could either redirect the attention of the individual on time (i.e., as the individual "avoids" the emotional stimuli) or distract the individual from time (i.e., as the individual is "attracted" by the emotional stimuli). In this case, the individual could either underestimate the duration (i.e., as she or he records fewer pulses as a result of distraction) or overestimate the duration (i.e., as he or she records more pulses as a result of their increased attention towards time). In relation to the arousal effect, the effect would be uniform across the situations because the arousal would lead to an increase in the pulse rate, thereby leading to an overestimation of the duration.

Concerning the model's reasoning systems, the explanation of emotional interference is more complex because this system regroups several distinct processes governing temporal cognition. Briefly, this system, compared with the updating one, is supposed to include information about the world not only as it is in the present, but also as it was in the past and may be in the future. Therefore, a creature able to use this system should be able to order events that occurred in the past, plan a future task in the correct order, and discriminate the recency of past events. Although the literature on these specific processes is scarce, research tends to point toward a disruptive effect of emotion, diminishing the ability for one to use this system. Indeed, Huntjens et al. (2015) showed that when presented with highly arousing pictures depicting a story (i.e., either positively or negatively valenced), participants had a harder time ordering them in chronological order. Furthermore, it has been found that experiencing a traumatic event can lead to a disrupted narrative of the event (e.g., among abused children; see Miragoli et al. 2017), which is supported by studies showing a disruptive effect of negative emotions on episodic memory (Bisby et al. 2018). Furthermore, traumatic events would tend to bias the temporal order of the event preceding and following the event itself (Byrne et al. 2001).

Interestingly, the separation between the updating and reasoning systems is relatively close to the separation between absolute and relative dating (Shimojima 2002). Absolute dating is when an individual uses the stored memorised date of an event to judge how much time has passed since the event, whereas the subjective timing refers to an approximation made without the use of the exact date. Shimojima (2002) demonstrated that although his participants knew the exact date of an event, and therefore the exact time that had since passed, they felt subjectively more or less time had passed since that event, indicating a discrepancy between the absolute and relative dating. Furthermore, Shimojima (2004) also demonstrated that emotionally charged events (i.e., whether negatively or positively valenced) would lead to discrepancies between absolute and relative dating, further supporting the disruptive effect of emotion. It is noteworthy that H&M's model mentions that discrepancies have been observed between the reasoning and updating systems, which could be supported by Shimojima's study (2004). These assumptions are also partially supported by the effect of emotion on episodic memory because it has consistently been reported that emotional events (Bowen et al. 2018; Kuriyama et al. 2010; Phelps & Sharot 2008), as well as the spatiotemporal context of these events (Schmidt et al. 2011), are more vividly remembered. Therefore, the absolute dating of such emotional events would be highly precise (i.e., the context being remembered more intensely), whereas relative dating would suffer from the telescoping effect (i.e., the tendency to underestimate the time passed since a distant memory; see Shimojima & Koyazu 1999; Thompson et al.1988), leading to a discrepancy between the two types of dating (i.e., resembling the discrepancies broached in H&M's model).

In this commentary, we have demonstrated that emotion could be incorporated as a major variable in H&M's model. The research outlined appears to fit in almost seamlessly for both systems in the model, although further research is required to fully explain how emotion and the reasoning system interact. Interestingly, the interaction between emotion and temporal cognition provides more explanation of the model's discrepancies between the two systems.

A theory stuck in evolutionary and historical time

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Abstract

We argue that the two temporal cognition systems are conceptually too confined to be helpful in understanding the evolution of temporal cognition. In fact, we doubt there are two systems. In relation to this, we question that the authors did not describe the results of our planning study on ravens correctly, as this is of consequence to their theory.

Hoerl & McCormack (H&M) let our study on raven planning exemplify studies measuring mental time travel (MTT) to the future. However, we did not investigate MTT, but conducted functional behavioural comparisons between apes and ravens, without directly inferring neurocognitive mechanisms (Kabadayi & Osvath 2017; Osvath & Kabadayi 2018). Such operational definitions are useful when comparing taxa vastly separated in phylogeny and brain constitution. It follows that we remained agnostic about whether ravens are temporal reasoners *sensu* H&M. It is perhaps not necessary to ascribe ravens' temporal reasoning based on this study, but H&M's claims are oversimplified. This reflects the conceptual narrowness of the two systems: updaters and reasoners. The distinction risks throwing out a whole kindergarten with the bath water.

H&M assert that our study failed to show that the ravens selected items for a situation they represented as distinct from the present, and that the delays played no role in their reasoning behind the selection. However, this is not true. H&M ignore a pivotal part of the study: the delay-based control, which teased apart whether the ravens selected the tool because it was immediately rewarding or because it carried value in relation to the non-present apparatus event. Two intertemporal choice experiments showed that the ravens exerted significantly more self-control in selecting the tool over an immediate reward if the apparatus event was closer in time (less than a minute compared with 15 minutes). This revealed, contrary to H&M's claims, that the delay played a crucial role in how the ravens selected and also that they represented the apparatus event as distinct from the current situation. In H&M's account, the ravens' behaviours are governed by what they call primitive goal representations. They illustrate this by a thought bubble in their Figure 2, which purportedly depicts the raven's reasoning: "The apparatus is somewhere in the environment. The stone operates the apparatus. Choose the stone" (Fig. 2, Temporal updating account). As the raven's representation does not include delays, it will produce the same thoughts regardless of any delays. Hence, the raven would select the item equally often despite differences in delays. Indeed, one would expect that the ravens would never even select the immediate reward, as it is smaller than the future one: In the mind of the raven there are, according to H&M, only two "immediate" rewards. The empirical results spell out something other than the thought bubble. So, what are the ravens doing?

We have already excluded primitive goal representations. The other option given for an updater by H&M is temporal sensitivity, which triggers a behaviour when a phase timing system is in a certain state. However, this does not work either, as there were no phases to time: two identical selection events, that could be offered anytime during the day, where only the *upcoming* delay differed. We are left with "elapsed-time sensitivity," which H&M used to explain how an animal senses that a certain time has elapsed. The problem here is that according to H&M, such sensitivity is experienced in the ongoing present; it is not represented afterwards. So, the selection event could not cue any memories of the different sensations that relate to the two different delays.

The explanation of the ravens' behaviours boils down to three possibilities: They did not do what they did; they are temporal reasoners; or they did something not captured by H&M's theory. As for the third alternative, one can think of many cognitively rich ways in which some animals could implicitly represent time, without representing time as such. If animals can be time sensitive, why could some not remember such sensations? If you have means-end reasoning why can you not represent change? (H&M seem to think that representing change is the same as representing it *as* change.) If they can represent locations in their inner map, why can they not represent distances? "Here" is not "there," and "there$_1$" is not "there$_2$," and reaching any of these locations requires different work effort, often related to time. (Many animals fancy shortcuts.) All sorts of memories of actions, sensations, or distances could become embodied representations, which are intrinsically related to time, without having a "pure" representation of the dimension itself. Such representations may differ widely between species.

Millions of species, with half a billion years of evolutionary history as animals, are lumped together as updaters, whereas only one is identified as a reasoner. H&M think that this distinction is more helpful than the dichotomy that often surfaces in MTT debates. Nevertheless, not only do they argue that MTT requires temporal reasoning; they still put forward a strong dichotomy. This is unhelpful for the study of the evolution of cognition. Ravens and great apes pass planning tasks that monkeys and young children do not. According to H&M, all these animals are incapable of representing time, which might be true, but then how is the distinction helpful in explaining striking differences between updating species? Relatedly, there is no account on how one evolves from an updater to a reasoner. The distinction is untimely when animal cognition research is increasingly directed at cognitive evolution beyond the very thin human lineage. It is not uninteresting whether some animals reason about time, but it is only one among a host of equally interesting questions. This rehashed "stuck in time hypothesis" comes across as stuck in the past.

As an endnote, one may ask whether this truly is a division between two distinct and conceptually equivalent systems. It seems, rather, that the authors use temporal updating just to explain the virtues of temporal reasoning. There appear to be many ways in which one can be cognitive about time without representing time, but only one in which one can be a temporal reasoner. This relationship is too unbalanced to warrant two categories. Moreover, temporal reasoning likely depends on the ability of abstract conceptualisation, which in humans is greatly aided by linguistic minds, and such conceptualisations pertain to a myriad of phenomena, where "time" is only one. This is not a temporal cognition system per se.

Identity-based motivation and the paradox of the future self: Getting going requires thinking about time (later) in time (now)

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Abstract

People can imagine their future selves without taking future-focused action. Identity-based motivation theory explains why. Hoerl & McCormack outline how. Present-focused action prevails because future "me" feels irrelevant to the choices facing current "me" unless future "me" is experienced as occurring now or as linked to current "me" via if-then simulations. This entails reasoning in time and about time.

People mentally time travel, imagining the person they might become. Yet they often fail to take sufficient future-focused action (Oyserman et al. 2012; 2017). Why might that be? Identity-based motivation (IBM) theory explains why. Thinking (about the self) is for doing. People's actions fit what their identities imply. At the same time, which identities come to mind and what these identities imply for meaning making and action is dynamically constructed given the situation at hand (Oyserman 2007; 2009). Future "me" is abstract, uncertain, and later, in contrast, present "me" is concrete, certain, and now. Hence, on-the-mind future possible identities matter, yielding future-focused action only if they feel relevant to the constraints and opportunities afforded in the current situation (Horowitz & Oyserman, under review; Oyserman & James 2009). Then, experienced difficulties starting and keeping going will be interpreted as implying that taking future-focused action is important – a for "me" or for "us" thing to do. Otherwise, experienced difficulties starting and keeping going will be interpreted as implying that future-focused action is impossible – a "not for me" or "not for us" thing to do, a waste of time.

Three different ways to trigger relevance are described in the literature (Horowitz & Oyserman, under review; Oyserman & James 2009). For ease of understanding, we term these "concretization," "assimilation," and "contrast." Concretization entails automatically associating specific strategies for action to future "me" –hence, concretization focuses on current action and future possible identities. Rather than considering future "me" and strategies for action, assimilation and contrast focus on future "me" and current "me." Assimilation entails including future "me" in one's mental representation of current "me." Contrast entails excluding future "me" from one's mental representation of current "me" and using future "me" as a standard against which to judge current "me." Each way of triggering relevance works. People are more likely to take future-focused action if their on-the-mind possible identities are linked to strategies for action, if future "me" feels close, connected to, or overlapping with current "me," and if they experience a gap between a separate current and future "me."

What is missing from this concretizing, assimilating, or contrasting account is a set of predictions as to when and how each is triggered. This gap can be addressed by synthesizing Hoerl & McCormack (H&M)'s dual (atemporal and temporal) reasoning systems perspective with IBM theory. H&M articulate two systems, a basic one that entails thinking *in time*, which they term the atemporal system, and a higher order one that entails thinking *about time*, which they term the temporal system. We use this atemporal and temporal framework to describe how and when an accessible (on-the-mind) future "me" can trigger future-focused action.

First, consider concretization, in which people imagine possible identities linked with strategies. Here people are simulating actions directly, "seeing" themselves working toward future "me" as if this action is taking place in the present (Oyserman & James 2009). In H&M's terminology, this concretization process takes place in the basic temporal updating system, which allows people to represent present actions and future "me" simultaneously in an atemporal landscape.

Second, consider assimilation in which people imagine future "me" as near, part of, or overlapping with current "me." Here, people are "seeing" the rewards of investing in future "me" as if these rewards were occurring in the present (Nurra & Oyserman 2018). In H&M's terminology, this assimilation process also takes place in the basic temporal updating system, which allows people to represent future goals and present goals simultaneously in an atemporal landscape in which the future and present have equal weight. This seeming simultaneous experience of the future and present facilitates the experience: "future me *is* me" and that allows people to forgo current for future consumption in situations in which motivational control is needed to privilege "later" over "now." Hence, reasoning within the temporal updating system is sufficient if future-focused action entails delay of gratification.

Third, consider contrasting in which people experience future "me" as distinct from a current "me" that serves as a goalpost. The temporal updating system is not sufficient to accommodate this mental simulation because the temporal updating system does not represent time. This means that future and current "me" cannot be represented independently, nor can the relative temporal distance of any simulated future "me." These aspects are necessary when the motivational force of future "me" comes from contrasting. To get going, contrasting requires that people mentally simulate a series of steps into the future with choices (forks along the way) and obstacles (roadblocks to be overcome) to move toward positive and away from negative future possible identities (Oyserman 2015). In H&M's terminology, this contrasting process takes place in the more abstract, culturally marked, temporal reasoning system. The temporal reasoning system facilitates mental simulation of a series of "if-then" statements (if a situation, then an action) on a linear timeline in which current "me" and a temporally distant future "me" are represented. Mental simulation allows individuals to start taking action and to preserve motivation at choice points, and when obstacles (failures along the way) occur.

Developmentally, the temporal updating system should be primary. It should be available even when the temporal reasoning system is not, for example, under cognitive load, and in other situations in which the capacity to reason abstractly is limited. These situations include risky contexts in which attention to "now" must be paramount. However, though the temporal updating system is sufficient to reason in time, the temporal reasoning system is necessary to reason about time, including reasoning about what a future "me" that is distinct from current "me" requires. We draw a number of important inferences from this distinction. First, people are less likely to take future-focused action if the ways in which they reason in and about time do not match the ways in which they imagine their future "me." Second, people are less likely to sustain future-focused action under cognitive load if they rely on contrasting for motivation, because contrasting requires the temporal reasoning system, which is less robust than the temporal updating system. Third, to be successful, interventions promoting future-focused action should match people's reasoning in and about time and the way they imagine their future "me."

No doing without time

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Abstract

Hoerl & McCormack claim that animals don't represent time. Because this makes a mystery of established findings in comparative psychology, there had better be some important payoff. The main one they mention is that it explains a clash of intuition about the reality of time's passage. But any theory that recognizes the representational requirements of agency can do likewise.

Humans live in a world imbued with time and temporal possibility, but Hoerl & McCormack (H&M) claim that animals don't. More precisely, although animals' representation of the world is *sensitive* to the passage of time, it contains no *representation of* time, and hence no representation of change, either. Such an account can perhaps explain how bees and other animals are able to return to a food source that becomes available at the same time each day. The animals can learn to associate the availability of food with the position of the sun in the sky. But how can animals lacking any representation of time learn an interval reward schedule, rather than one linked to time of day? Bumble bees can do this (Boisvert & Sherry 2006), as can hummingbirds, who can learn the varying rates with which different types of flower replenish their nectar, timing their visits accordingly (González-Gómez et al. 2011).

H&M allow that animals have various clock-like mechanisms that change regularly with the passage of time. But it remains mysterious how these mechanisms could issue in interval learning without time being represented and remembered. Suppose that a hummingbird visits a flower, finds it full of nectar, and drains it. It therefore forms a representation of the world as containing no nectar at that location. After 20 clicks of its internal clock, it happens to revisit the flower believing it to be empty, but finds it full, again draining it. Then, after 10 clicks of its internal clock, it happens to revisit the same flower again (why?), and finds it almost empty. If its internal clock gives rise to representations of time, the bird can now store the information that the flower takes between 10 and 20 clicks to replenish. But if it can't, how does the bird learn to visit the flower in the future when 20 clicks have elapsed, but not when only 10 have? Somehow, the ticking of its internal clock must cause its representation of the flower as empty to flip to representing it as full once significantly more than 15 clicks have elapsed (but after some other number of clicks for a different type of flower). We have no idea how H&M think this is supposed to happen, and would welcome clarification.

Moreover, there has been an immense amount of theorizing and successful data-collection within the broad framework of optimal foraging theory (Pyke 1984). It is generally assumed that an animal's decision to leave one patch for another depends on a comparison between the rate of reward at the current patch with the average rates previously experienced, together with an estimate of travel-time between patches. But a rate is a measure of quantity per unit of time. And indeed, it turns out that animals can be extraordinarily good at estimating rates, and adapting swiftly to changes in rates (Gallistel & Gibbon 2000; Gallistel et al. 2001). This literature assumes that animals can represent the passage of time, integrating representations of time with representations of quantity to issue in an estimated rate. It is mysterious to us how any of this could be done *without* representing time. How is the clicking of a body clock supposed to give rise to a representation of rate unless it can give rise to representations that can be integrated with representations of quantity? Here, too, we would welcome clarification.

Because H&M's claims seemingly require overturning established science, there had better be some important payoffs from accepting their view. One thing they discuss that is of particular interest to us is that their dual-systems view can explain the existence *and* persistence of certain contradictory elements in people's naïve theory of time. In their account, adults' temporal reasoning system, representing reality as temporally extended, implies that the present is but one temporal perspective among many (hence not ontologically privileged). Yet the temporal updating system, representing reality in a non-temporally qualified manner, produces what might be called a "present bias" that views the present as ontologically special. Importantly, because the temporal updating system is the more primitive of the two, it works automatically, delivering its verdict despite contradicting the more sophisticated temporal reasoning system. It therefore explains why even philosophers and physicists who are convinced that time does not really pass, still find time's passage intuitively irresistible.

However, a dual-systems approach isn't needed to explain the contradictory elements in people's naïve theory of time. As an alternative possibility, suppose that only the temporal reasoning system is at work. Its representation of reality has time as one of the dimensions, of which any subjectively indexed present moment is but one among many "locations." Such a representation, generated by temporally bound agents with temporally sensitive goals and desires, should recognize the distinction between past, present, and future in an agent-relative way. Indeed, H&M allow that the temporal reasoning system represents temporal order and tense. Once this much is permitted, the present bias can simply arise as an adaptation for successful action planning and execution *within the temporal reasoning system*, for the present marks the boundary between what cannot be changed (past) and what humans as intentional agents can still exert causal influence on (future). Plausibly, acting or planning to act *at the present time* is conducive to bringing about desired changes, which are themselves aimed for, *given the present state of the world*. It is therefore adaptive to include in one's temporally extended representation of reality the asymmetry of causal influence (Horwich 1987; Kutach 2011). The present then becomes privileged as a result of the requirements of agency.

In the alternative just sketched, it remains true, as H&M highlight, that people often cannot dislodge the impression that the present exists *simpliciter*, without temporal qualification. But our alternative does not posit a primitive system that fails to represent time per se. Rather, it is that it is adaptive to prioritize addressing present needs and challenges, even at the cost of representing past and future as "less real." In this sense, the persistent present bias might well be an "adaptive misbelief" à la McKay and Dennett (2009).

Dual systems for all: Higher-order, role-based relational reasoning as a uniquely derived feature of human cognition

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Abstract

Hoerl and McCormack demonstrate that although animals possess a sophisticated temporal updating system, there is no evidence that they also possess a temporal reasoning system. This important case study is directly related to the broader claim that although animals are manifestly capable of first-order (perceptually-based) relational reasoning, they lack the capacity for higher-order, role-based relational reasoning. We argue this distinction applies to all domains of cognition.

Hooray for Hoerl and McCormack's (H&M's) project on temporal cognition (TC). Their distinction between "temporal updating" (TU) and "temporal reasoning" (TR) adeptly demonstrates the sufficiency of the lower-order system, TU, to explain the TC of animals. To modify a trope from Dan Dennett: *In order to keep perfect track of the changing states of affairs in the world, it is not requisite to know a thing about time* (see Dennett 2009, for a discussion of Charles Darwin and Alan Turing's similar and respective "strange inversions of reasoning").

Povinelli and colleagues have previously shown that H&M's analysis, *mutatis mutandis*, holds true across most (if not all) other domains of cognition (Penn et al. 2008). Their "reinterpretation hypothesis" (RH) was initially advanced to explain the evolution of social cognition, and its central claims tightly parallel H&M's account of TC (Povinelli & Giambrone 1999; Povinelli & Vonk 2004):

1. Human social cognition is composed of phylogenetically ancient mechanisms for reasoning about behavior (analogous to those that H&M describe for the TU system), and a uniquely human system that reinterprets those behavioral relations in terms of abstract mental states.
2. The two systems continue to operate in concert in modern humans.
3. The newer system is dependent on the older one, but the causal power of the older system can completely explain the results of tests with animals.
4. Because of (3), RH is not an ad hoc alternative to higher-order accounts of animal social cognition.

The RH was later extended to other domains of cognition, including concept formation, physical causality (tool use), reasoning about weight, and even TC (Povinelli 2000; 2012; Vonk & Povinelli 2006). Finally, Penn et al. (2008) specified the domain general format of the RH, arguing that the ability to cognize over higher-order, role-based analogical relations is a uniquely human capacity cutting across every domain of cognition.

In this view, "time" is one of myriad, higher-order relations the human mind constructs. The bedrock distinction of TR is the ability of humans to group innumerable (indeed, any) individual perceptual relations (leaves falling, sands running through an hourglass, gray hairs erupting on one's head, etc.) as *temporal r*elations. H&M note that the human naïve (or folk) theory of time is yet to be fully explicated, and offer the interesting claim that one feature might be the idea that time "flows." This may be true, but all human babies share the capacity to be enculturated into any theory of time (scientific or otherwise). Why? Because the human mind allows for disparate perceptual relations to be grouped under common thematic or argumentative roles—a hallmark signature of all higher-order, role-based relations (Penn et al. 2008).

Since the most general statement of the RH was published in the pages of this journal a decade ago, dozens of empirical studies with animals have challenged the view that only humans reinterpret first-order perceptual relations in terms of higher-order relations. But all the demonstrations we have examined suffer from the same logical limitation that Povinelli and colleagues (and herein, H&M) have identified—namely, that first-order relational reasoning is necessary, but not sufficient for higher-order relational reasoning:

Same/different judgments?

Animals are presented with a sample of two (or more) objects that are either all the same (AA) or different (BC), and then can learn to select alternatives that match the relation (i.e., DD or EF). Are such performances evidence that animals possess the higher-order relations of *same*/*different* as some have claimed (e.g., Flemming et al. 2013)? No, because to form such higher-order relations, a cognizer must first detect the amount of perceptual variability in the displays (zero variability for *same*, higher variability for *different*). Once such perceptual variability is detected, however, this information can be used to sort novel exemplars.

Spatial analogies?

Haun and Call (2009) claim that chimpanzees can recognize relational similarity between perceptually distinct predictors of food location. Subjects were confronted with a tilted table that contained three equally spaced out beyond their reach ("far") cups and three within reach ("near") cups. The second and third near cups were increasingly spatially misaligned with the far cups. In one condition, opaque tubes connected the experimenter's cups to the subjects' cups. In another, painted lines "connected" them. The chimpanzees saw food dropped in a far cup and successfully searched in the near cups that were connected by the tubes or the lines. These apes were clearly tracking spatial relations (e.g., "if food is placed to extreme right, orient to that side" or "if cups are touched by a tube, pick it"), but there is no reason to think they constructed an analogy between the spatial relations of lines and tubes as suggested by the authors. Christie et al. (2016) recently claimed that chimpanzees are sensitive to the spatial analogy between a three-tiered shelf and another, identical one located nearby. While this is evidence that space guides searching ("food located low, continue to search low"), it is a far cry from higher-order relational reasoning.

Analogy in tool use?

Taylor et al. (2007) demonstrated that crows use a short stick to retrieve a longer, functional stick. They suggest the crows may have done so by cognizing over the causal analogy between short and long sticks ("tools access out of reach objects"). This task may or may not be "cognitively demanding," but it can certainly be solved by detecting the spatial distance between the subject and the goal object and the length of the stick.

Theory of mind?

Bugnyar et al. (2016) showed that ravens that hear (but do not see) a conspecific in an adjoining room are sensitive to the presence/absence of a small hole in the wall between the rooms. They interpret this as evidence that the subjects can imagine the mental state of the other raven *seeing* them. This experiment was designed to rule out the deflationary account of previous studies, wherein animals need only track and use the relations between conspecific location and unobstructed geometric paths. But there is nothing higher-order about an organism constructing a geometric relation based on "hearing" (as opposed to "seeing") a nearby conspecific.

A flood of additional claims for higher-order thinking in animals have surfaced on topics such as the appearance-reality distinction, metacognition, intentional communication, water displacement, logical inference, false beliefs, love, morality, maps, gravity, altruism, mourning the dead, self-recognition, teaching, cooperation, and physical cognition (Povinelli & Barker 2019). We contend each of these claims can be dismantled in the manner that H&M have for TC, and we have done for other cognitive domains.

Given that such a straightforward issue lies at the heart of innumerable confusions in animal cognition (Penn & Povinelli 2009), why is it consistently ignored by comparative psychologists? While we encourage others to remain hopeful that H&M's master class on TC will lead to a sudden sea change, we remain cautious. Is there something so folk-psychologically compelling about tales of higher-order thinking in animals that even scientists cannot escape them? If so, comparative psychologists may well go on telling such animal tales as long as humans go on telling stories (Barker & Povinelli 2019). H&M's heroic efforts would then be destined to sink into the mythic sea of "lost knowledge"—that ever-receding ocean of hard-won truths humans are fated to continually rediscover.

Locating the contradiction in our understanding of time

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Abstract

I offer some clarification concerning the kind of contradiction that Hoerl & McCormack's account could help explain and the scope of the metaphysical intuitions that could be explained by such a theory. I conclude that we need to know more about the sense in which the temporal reasoning system would represent time as a dimension.

Hoerl & McCormack (H&M) say that "there is an inherent contradiction in people's naïve theory of time, insofar as it contains within it both the belief that there is an objective present and the belief that which moment in time is objectively present changes" (sect. 4, para. 6). They suggest that their two-system account helps explain this. But although I think there is something to be said for their proposal, the contradiction that they explain is different from the one that they say they are going to explain.

The latter contradiction arises because of the alleged conflict between the claim that the present time has a unique, privileged status and the claim that every time momentarily becomes present as time passes. It cannot be true that all times are present, and that only one time is present. As H&M suggest, this is one way of capturing the contradiction that J. M. E. McTaggart (1908) suggested lay in the very notions of past, present, and future.

There is a standard response: No contradiction arises in our naive view because, according to that view, only one time is present *at any given time*. H&M say that this reply fails because "it makes which moment in time is present dependent on what time it is considered from, rather than it being an objective property of time which moment is present" (sect. 4, para. 7). But this reply would not satisfy the advocate of the naive view. For they hold that when time passes, reality, as a whole, changes; a different time becomes present. This change does not correspond merely to a difference in perspective; it is an objective change in reality. No two times are present within a single reality, so there is no contradiction.

The contradiction that H&M subsequently explain does not, however, appear to be the one whose existence I have just denied. Instead, it is a contradiction between the claim that there is just one moment in time, with past and future times not being real, and the claim that all times are equally real. This does not concern presentness; it concerns ontology, or what exists. Their suggestion is that because the temporal updating system represents only the present time, and deals with changes just by updating its model of the present, it disposes us to think that the content of the model is all that is real. The temporal reasoning system, by contrast, represents the whole time series, and therefore drives the intuition that all times are real.

It is worth mentioning some relevant theories in metaphysics. According to *presentism*, reality is not extended in time, and consists only of the present, whose features change as time passes. So the temporal updating system would embody the presentist view of reality, and explains the intuition that drives it. According to *eternalism*, by contrast, reality is extended in time, and all times are equally real. The temporal reasoning system therefore models an eternalist metaphysics.

Not all eternalists deny that time passes, however. Some, known as *moving spotlight* theorists, hold that each time undergoes constant changes in the extent to which it is past, present or future. The fact that such views are possible, and sometimes advocated, must cast some doubt on whether the two-systems theory can explain the sense of time passing, rather than explaining just the ontological intuition that only what is present is real (though this would still be progress).

Presentists do not deny that there are truths about the past or future. They typically hold that reality should be described using the operators of tense logic, such as 'in the past.' Hence, the past occurrence of rain is represented as 'in the past: it is raining.' This corresponds to one version of our naive view of time: Only the present is real, but it is nonetheless true to say that various things have happened, or will happen. Does the temporal reasoning system provide a representation that conflicts with this naive view? It is not clear that it must do so, to provide cognitive benefits relative to the temporal updating system. The temporal reasoning system represents times in an order, perhaps with a metric. But this would be true even if the representation were from the perspective of the present, with descriptions of events at other times preceded by the appropriate tense operators. Because this is compatible with presentism, it ought not to contradict the representation of the temporal updating system.

To produce the relevant ontological contradiction, then, what is needed is a representation of time as a *dimension*, an extended region of reality all of whose parts exist equally. Contrast this with, say, a system of representation of voltages and currents in an electrical circuit. When one plots a graph of voltage against current, one does not thereby draw a map of an extended region of reality. But when one plots a region of space along two axes, one does draw such a map. The difference lies not in the system of representation itself, which in both cases involves an ordering and a metric, but in the way in which this representation is interpreted.

H&M do describe the temporal reasoning system as representing time as a dimension, but they do not say much about what makes this the case. Perhaps one important factor would be the ability to represent the time series from no specific point of view (and therefore without representing times in terms of tense-properties such as *past*; note the impossibility of a corresponding representation in the voltage/current example, with axes that do not represent properties). This raises the question of whether there could be an intermediate case in which a creature has a reasoning system that represents a series of times identified by their tenses, allowing cognitive advantages over a creature with only a temporal updating system, but without the decentered, 'no-perspective' representation that would contradict the presentism suggested by the temporal updating system.

Thinking about thinking about time

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Abstract

Hoerl & McCormack (H&M) discuss the possible function of meta-representations in temporal cognition but ultimately take an agnostic stance. Here we outline the fundamental role that we believe meta-representations play. Because humans know that their representations of future events are *just* representations, they are in a position to compensate for the shortcomings of their own foresight and to prepare for multiple contingencies.

The capacity to entertain meta-representations has long been central to theorising about mental time travel (Suddendorf & Corballis 1997). In its original and most narrow sense, meta-representation is defined as representing the representational relation between a representation and its referent (Pylyshyn 1978). Hoerl & McCormack (H&M) argue that this capacity may not necessarily be implicated in grasping temporal relations between different models of reality from the same time line (sect. 3.2, para. 9) – such that tonight's dinner will follow the breakfast you are eating now. Still, we contend that meta-representations play a fundamental role in grasping relations between different models of reality from *alternative* time lines.

H&M allude to alternative time lines when they write about "bifurcation points in linear time" (sect. 5, para. 8), where multiple possible outcomes of an event diverge (e.g., a coin flip). Yet H&M's model includes no mechanism for how such bifurcation points could be understood. We suggest that the capacity to form meta-representations is critical. A meta-representational agent can understand that representations of events are *just* representations and that they do not always map onto referent events in a one-to-one fashion (Perner 1991). With this understanding, the agent can infer that a single representation of an event outcome only maps onto *one* of all possible outcomes for that event (Redshaw 2014). The agent can also tag such representations with evaluations, such as how likely they are to transpire, whether they are best or worst case scenarios, and whether they may be exaggerations (Suddendorf 1999; Suddendorf & Corballis 1997; 2007b).

The capacity to form meta-representations can explain why humans not only envision and prepare for likely and desirable future outcomes, but also implement contingency plans (Redshaw & Suddendorf 2016). When planning an overseas holiday, for example, we might book flights and hotels, but we typically also buy travel insurance just in case things take a turn for the worse. Meta-representations may also underlie certain cases of delayed gratification that are not easily explained by the two mechanisms H&M invoke. When beginning a diet, for example, we may imagine a future in which we eat only healthy food. But when we meta-represent that this is just *one* possible future, we can make it more likely to manifest by removing temptations such as the junk food in our pantry. To generalise, meta-representations enable at least two pervasive types of future-oriented human behaviour: (1) preparing for multiple possibilities to compensate for the fact that we do not know exactly what will happen, and (2) structuring our current environment in such a way so as to increase the likelihood that desirable versions of the future will transpire. In Bulley et al. (in press), we introduce the term *metaforesight* to describe the cognitive processes that drive such behaviour.

The recursive capacity to embed representations within other representations also allows humans to entertain hierarchically nested levels of temporal reasoning. To illustrate: At the first level, we recognise that a future event can have multiple possible outcomes. At the second level, we might reflect on the fact that a past event {level 2} once had such multiple possible future outcomes {level 1}, which is central to the emotional experiences of regret and relief (Hoerl & McCormack 2016). At the third level, we might imagine a future situation {level 3} in which we will reflect on the fact that a past event {level 2} once did have multiple possible future outcomes {level 1}. This understanding is central to emotional experiences like *anticipated regret*, which can drive actions such as putting away that second bottle of wine to prevent a regret-filled hangover tomorrow. Recursive operations are in principle unbounded, and so humans may be limited primarily by working memory constraints on the number of levels of temporal reasoning they can entertain. Accordingly, alongside increases in working memory capacity (Alloway et al. 2006), children become able to prepare for multiple future possibilities (Beck et al. 2006; Redshaw et al. 2019) before they appear to experience regret (O'Connor et al. 2012), which in turn appears to develop before they can anticipate regret (McCormack & Feeney 2015).

Notably, these nested levels of temporal reasoning are not restricted to situations where future and past perspectives are *both* represented. Rather, we can recursively imagine future situations in which the future will be imagined, such as when we *worry that we will keep worrying* (Wells 2005). So too, can we reflect on past occasions in which the past was remembered.

Non-human animals' foresight may be restricted by deficits in various components contributing to mental time travel (Suddendorf 2013; Suddendorf & Corballis 2007b). If they cannot form meta-representations (Carruthers 2014; Suddendorf 1999), then they might find it difficult to prepare for multiple possible versions of uncertain future events (Redshaw 2014). Preliminary evidence is consistent with this prediction, with studies failing to find any evidence that non-human great apes can spontaneously and consistently prepare for mutually exclusive outcomes of even a very simple, immediate future event (Redshaw & Suddendorf 2016; Suddendorf et al. 2017). In one recent study (Lambert & Osvath 2018), chimpanzees were more than seven times more likely to prepare for two certain future outcomes than for two uncertain future possibilities – even though the optimal response across conditions was exactly the same (see Table 1 of that article). Performance in both conditions was relatively poor, however, and so further work with other paradigms is warranted.

Evidence for other forms of complex prospection in animals also remains controversial (Suddendorf et al. 2018; Suddendorf & Redshaw, in press). Although some high-profile studies have claimed that great apes (Mulcahy & Call 2006) and corvids (Kabadayi & Osvath 2017) can select objects with the intention of using them to obtain rewards in future situations, these have been criticised for failing to control for low-level explanations such as associative learning (Hampton 2018; Lind 2018; Redshaw et al. 2017; Suddendorf & Corballis 2008). H&M state that criticising such studies on individual "ad hoc" bases may be unconvincing, but we maintain it is important for progress to clarify in each case why the conclusions are not compelling and what kind of controls could provide stronger evidence.

NOTE

1. There was a misspelling in Adam Bulley's second affiliation in the original online version of this commentary. This has been corrected here and an erratum has been published.

The dual systems in temporal cognition: A spatial analogy

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Abstract

The model presented by the authors can explain an inherent contradiction in people's naïve theory of time. In this commentary I suggest a way in which another paradox of our phenomenal temporality may be addressed along these lines. In the final section, I also discuss some concerns that may arise about the clear-cut distinction between humans and non-human animals.

When we reflect upon our phenomenal temporality – the way we experience the passage of time – we are presented with a number of apparent contradictions. One of the most striking is that, in a sense, the present is special – it is the only real moment that we directly experience. However, this privilege is almost instantaneously transferred to another moment, which then becomes the present, and so on. In a slogan, the problem is that if every moment is special, then no one is. This problem is addressed in a very promising way by the dual systems presented by the authors. The idea that adult humans retain a temporal updating system – a sort of timeless picture of what there is out there – alongside a temporal reasoning system, could explain the apparent paradox of having contradictory beliefs about the present. In this commentary I propose an analogy with another apparent paradox concerning our phenomenal temporality, presenting a similar dual systems perspective, and I tentatively suggest a way in which this other paradox may be explained in Hoerl & McCormack (H&M)'s view. In the final section, I also discuss some concerns that may arise about the clear-cut distinction between humans and animals.

Consider another apparent paradox of our temporal phenomenology. When we hear two gun shots (say 100 ms from one another), we have *one* experience of *two* sounds. We do not experience the first "as past'" when we hear the second. Nonetheless, when after some seconds we think about what happened, we know that one shot was *before* the other – we remember a sequence of temporal ordered sounds; the single experience of the two shots felt in the present is lost. But if we *know* that the present is technically point-like, and if we *remember* the two sounds as temporally diachronic, why do we experience them as temporally synchronic – part of the same phenomenological present? Maybe the simplest option is the right one. If we experience two such different things, it could be because there are two different cognitive processes going on. In Roselli (2018), I have proposed an analogy with a spatial debate, in which two distinct ways of operating our intellect – counting and subitizing – were distinguished. The word "subitizing" (Kaufman et al. 1949) refers to the immediate visual capture of a certain number of items, to be distinguished from the usual action of counting. Experimental results (Camos & Tillmann 2008; Trick & Pylyshyn 1994) showed a significant difference between judgments made for displays composed of one to four items and for displays of more items. Of course, response times always rise when the number of items showed is increased, but there is a dramatic difference between the two groups. I have argued that even in the temporal case there may be at work two different processes: Whereas a temporal subitizing is responsible for our directly experienced present (a single "temporal look" at an extended period of time, that comprises a succession of more sounds in an immediate co-conscious present temporal experience), a temporal counting has the more elaborate cognitive task to store in succession the auditory stimuli perceived.

Would it be possible to re-describe this solution to the "paradox of the present" in H&M's terms? Their dual systems approach could describe the extended phenomenological presentness as a result of the temporal updating system, whereas the temporal reasoning system would be responsible for the successive awareness of an after-before relation *within* that experienced extended present. As they point out, even if children are able to reproduce actions in the right order, this ability in itself is something that can fall within the scope of the temporal updating system. It is reasonable to assume that even in such cases what children have in mind is an extended present experienced in a certain way, rather than a temporal succession in which past, present, and future are distinguished. It is only thanks to the temporal reasoning system that we put events in a genuine temporal order and are aware of what that means. If the analogy holds, it is a very good sign for the authors' system, because it would mean that another apparent paradox of our temporal phenomenology could be explained in the terms of their dual systems perspective.

Finally, I want to briefly discuss a potential source of concern. The authors claim that neither animals nor infants can think and reason about time, and that they can merely change their representation of the world as it is, instead of representing change. Two different systems of cognition are described, and a clear-cut distinction between humans (adult and sane) and other animals is drawn. This is, however, at least *prima facie*, problematic; do humans really have something that *all* the other species do not have? It is very likely that ants do not "represent change" in any meaningful sense but what about dolphins or chimpanzees? Note that not every human is intelligent in the same way. Where should the line be drawn? I am not convinced that it is possible to claim that all non-human animals are stuck in time. H&M admit that some birds "have timing mechanisms that would allow them to be sensitive to the length of a 124-hour period (or even longer)" (sect. 2.1, para. 3). But when a timing mechanism becomes so long, is it really possible to distinguish it from a "primitive" temporal reasoning? I suspect that examples coming from studies with primates could give even stronger cases for this (Savage-Rumbaugh & Lewin 1996). It may be too much to claim that "animals are not capable of thinking about the past or the future at all" (sect. 6, para. 2). A chimpanzee's temporal reasoning system is probably a lot weaker than ours, but is it enough to draw a clear-cut line between humans and non-human animals?

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What time words teach us about children's acquisition of the temporal reasoning system

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Abstract

Here I consider the possible role of the temporal updating system in the development of the temporal reasoning system. Using evidence from children's acquisition of time words, I argue that abstract temporal concepts are not built from primitive representations of time. Instead, I propose that language and cultural learning provide the primary sources of the temporal reasoning system.

In Hoerl & McCormack's (H&M's) dual systems account of temporal cognition, the primitive mechanisms and mental representations involved in "temporal updating" are not sufficient for "temporal reasoning." A key question about the relationship between the two proposed systems is not fully addressed, however. What role, if any, do mechanisms of temporal updating play in the subsequent development of the temporal reasoning system? Despite being insufficient to support mature temporal reasoning on their own, evolutionarily ancient representations of time could nonetheless provide the initial building blocks from which the temporal reasoning system is built. Here, I will present developmental evidence suggesting that this is not the case. Instead, I propose that language and culture are the primary sources of the abstract conception of time.

Before addressing the sources of the temporal reasoning (TR) system, we must be clear about the nature of this system. H&M discuss many capacities, such as mental time travel, which they argue are only allowed by the TR system. Here, however, I will focus on their central claims about the format of this representational system itself. Specifically, they describe a model of "time itself" that is linear, unidirectional, and includes a conceptual distinction between the past and future. I concur with the assessment that there is currently no compelling evidence that non-human animals or human infants possess such a model of time.

How might the TR system be constructed in the mind of a child, and what are its developmental sources? Importantly, H&M do not claim the dual systems are completely independent of one another. They allow that mechanisms involved in the temporal updating system can also be involved in temporal reasoning, and, further, that they may "ground" the TR system. This idea bears similarity to existing theoretical accounts of abstract concept acquisition in which innate, perceptual primitives play a critical role (Carey 2009; cf. Barner 2017). On the dual systems account, temporal updating processes cannot be the *only* source of TR. However, the account is consistent with the possibility that primitive temporal representations – for example, of duration and order – provide the source material for the subsequent development of TR. Relatively little attention is given to other potential sources.

By examining how adult ways of representing time are initially understood by children, we may uncover clues about the developmental origins of TR. In industrialized cultures, adults constantly engage in TR by using explicit symbolic systems. We use words to describe and label different aspects of "time itself," and we use artifacts like clocks and calendars to visually represent an invisible temporal dimension. Learning to use these symbolic systems is slow and arduous, and many children continue to struggle with this long after the 3- to 5-year-old developmental window that is the focus of the target article (Friedman & Laycock 1989;

Kamii & Russell 2012). Nonetheless, children start learning early, and even 2-year-olds produce abstract, time-related words (Ames 1946).

As H&M point out, simply being able to say temporal words should not be taken as evidence that children fully understand them, or that they have TR capacities that would allow this. Relevant to this, beyond the early studies of "before" and "after," more recent research has examined children's acquisition of additional classes of time words (Busby & Suddendorf 2005; Busby-Grant & Suddendorf 2011; Shatz et al. 2010; Tillman & Barner 2015; Tillman et al. 2017; Zhang & Hudson 2018a). These other lexical categories are linked to key facets of the adult TR system. For example, our use of duration words, like "minute," implies that time is an absolute, measurable dimension. Deictic time words, like "yesterday," reference non-present locations in a linear temporal array, and (in English) are specific to the past or the future. In each case, there are multiyear gaps between children's first usage and eventual adult-like comprehension. However, as discussed below, children's early errors with time words are non-random, and reflect a gradual accumulation of knowledge about the temporal domain.

Most relevant to the dual systems perspective, studies of time-word learning suggest that primitive representational systems may play little, if any, role in the initial construction of symbolic representations of time. The first aspects of time-word meanings that children learn are precisely those that H&M argue the temporal updating system cannot support. For example, preschoolers infer that time words reference the domain of time; that they have systematic, ordered relationships with other time words, and that they reference either the past or the future (Harner 1975; Shatz et al. 2010; Tillman & Barner 2015; Tillman et al. 2017). In contrast, most children do not appear to map these words to perceptual representations of duration until two or three years later (Tillman & Barner 2015). This trajectory suggests that the updating and reasoning systems may be more independent than H&M suggest.

If children are not using primitive temporal representations, what sources of information do they use to acquire the TR system? The facets of time-word meaning that are most readily learned by children are those most easily inferred from adult speech, indicating that linguistic and narrative structure may support the acquisition of abstract temporal concepts (Tillman et al. 2017). Further, children's knowledge of exact definitions drives their ability to link time words with approximate temporal durations, suggesting that formal education may be a requirement (Tillman & Barner 2015).

In the target article, language and education are only briefly discussed, and cultural differences in temporal cognition are largely characterized as embellishments of a universal view. However, recent research on the effects of language, literacy, and education on mental representations of time suggest that they play a significant role (Bergen & Lau 2012; Boroditsky & Gaby 2010; Brislin & Kim 2003; Hendricks & Boroditsky 2017; Tillman et al. 2017). Moving forward, developmental scientists must continue to explore the specific roles of language and cultural transmission in early TR. In our quest for the psychological origins of time, these factors may prove more important than forms of representation shared with animals.

Neural correlates of temporal updating and reasoning in association with neuropsychiatric disorders

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Abstract

Here we argue how Hoerl & McCormack's dual system proposal may change the current view about the neural correlates underlying temporal information processing. We also consider that the concept of the dual system may help characterize various timing disabilities in neuropsychiatric disorders from the new perspective.

Hoerl & McCormack (H&M) have proposed to distinguish between "temporal updating system" and "temporal reasoning system" to interpret comparative and developmental psychological findings about temporal information processing. On the one hand, we understand that their view is compelling, especially from the viewpoint of developmental psychology. On the other hand, they stayed away from discussing the neural correlates that may underlie the two systems. They did not discuss how the proposed view might influence interpretations of findings from clinical studies on temporal processing in neuropsychiatric disorders, either. Hence, we will discuss plausible neural correlates, which may underlie the temporal updating/reasoning systems, and dysfunction of these systems, which may yield altered temporal processing in neuropsychiatric disorders. The argument is based on empirical evidence obtained in behavioral and neuroimaging studies (including our own) conducted in humans.

Previously, we performed a few neuroimaging studies to gain insight into the neural substrates underlying temporal information processing in healthy humans (Aso et al. 2010; Bushara et al. 2003; Ohki et al. 2016). Of particular relevance, Aso and colleagues studied neural networks underlying judgment and reproduction of time intervals in the range of hundred milliseconds to a second. The judgment and reproduction tasks were supposed to unveil neural mechanisms underlying sensory aspects and motor aspects of temporal processing, respectively. Although participants had to represent time intervals for a few seconds, the task did not necessarily require the representation of time as a dimension. Therefore, the task was likely subserved by the temporal updating system rather than by the temporal reasoning system. We found that both sensory and motor temporal processing involved cerebro-cerebellar networks. The key cerebral structure seemed to be the supplementary motor area (SMA), which was assumed to serve as a time controller sending timing signals to effectors and other brain regions (Aso et al. 2010). The cerebellum was assumed to receive an efference copy of the timing signals and to serve as an "emulator" for both motor and sensory tasks (Grush 2004). The SMA also has a connection with the basal ganglia (Hanakawa et al. 2017), which are implicated in temporal information processing in the range of seconds to hours (Ivry 1996). It is therefore possible that the motor cortical-basal ganglia-cerebellar networks support the temporal updating system. Consistently, Miyazaki et al. (2016) reported the neural correlates of tactile temporal order judgment and found the involvement of the motor system (ventral and bilateral dorsal premotor cortex and posterior parietal cortex) in temporal information processing.

The neural architecture supporting the temporal reasoning system, if any, is less clear. Presumably, the temporal reasoning system is supported by long-term memory and needs a higher level of cognitive processes than the temporal updating system. Gilead et al. (2013), found that the use of future tense is associated with ventromedial prefrontal cortex. Similarly, evocation of past and future events induces brain activation in the medial prefrontal cortex, cuneus/precuneus, and the medial temporal lobes (Botzung et al. 2008), which overlap with the default mode network. The default mode network comprising of the medial prefrontal cortex and medial/lateral parietal cortex is implicated in representing autonoesis, which should be closely related to the function of temporal reasoning system. Nevertheless, the default mode network exists in both humans and animals. Growing evidence suggests that the rostro-lateral prefrontal cortex (or frontopolar cortex) may represent the past and the future to guide goal-directed behavior (Tsujimoto et al. 2011). Because the rostrolateral prefrontal cortex is particularly developed in humans, the development of this cortical structure may provide an account for the capacity of temporal reasoning uniquely in humans as claimed.

Dysfunctions of the neural correlates of the temporal updating and reasoning systems may underlie abnormality in temporal information processing in neuropsychiatric disorders. Dysfunction of the SMA-basal ganglia network (Hanakawa et al. 2017) may account for abnormality in temporal information processing in Parkinson's disease (Ivry 1996). Evidence indicates that patients with schizophrenia may have impaired temporal updating systems, having difficulty in interval discrimination, and temporal prediction tasks (Waters & Jablensky 2009; Takeda et al. 2017; Ueda et al. 2018). Losak and his colleagues (2016) examined brain activity during a predictive timing task, which would concern the temporal updating system, in patients with schizophrenia. They found alteration of brain activity in several brain regions including the SMA and cerebellum, which again support the role of the motor cortical-basal ganglia-cerebellar networks in the temporal updating system. In a meta-analysis by Thönes & Oberfeld (2015), timing task performance, which would mainly concern the temporal updating system, showed no significant effects of depression.

Neuropsychiatric disorders may also have altered temporal reasoning systems, but much remains to be studied. Patients with schizophrenia may have distortion in the temporal reasoning system, presumably involved in prospective memory and mental time traveling (Fornara et al. 2017; Henry et al. 2007). Recently, some investigations elucidated that patients with depression might have impairment in the temporal reasoning system. For example, patients with depression show increased use of past tenses, reduced vividness of positive prospective memory and negative beliefs about the future (Morina et al. 2011; Roepke & Seligman 2015; Smirnova et al. 2018). Abnormality in subjective speed of time flow, which is likely subserved by the temporal reasoning system, has also been implicated in bipolar disorders and depression (Northoff et al. 2018; Ratcliffe 2012). Neural substrates underlying these abnormalities should be investigated more vigorously than now, under the concept of the dual systems.

H&M's dual system proposal may provide new account for the timing deficits observed in neuropsychiatric disorders. Further research will be needed to delineate the nature of the temporal information processing in neuropsychiatric disorders and responsible sites of regions/networks.

Animals are not cognitively stuck in time

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Abstract

We argue that animals are not cognitively stuck in time. Evidence pertaining to multisensory temporal order perception strongly suggests that animals can represent at least some temporal relations of perceived events.

Hoerl & McCormack's (H&M's) dual system approach to temporal cognition holds that animals cannot represent temporal properties of events given the limitations of the temporal updating system. But even if H&M are right that animals are not capable of mental time travel (MTT) and lack certain forms of episodic representation, there are other forms of temporal representation that they are likely to possess. In this commentary, we argue that considerations having to do with *multisensory temporal order perception* strongly suggest that animals are not cognitively stuck in time.

In adult humans, MTT and related capacities for episodic thinking are dissociable from more rudimentary perceptual capacities for keeping track of time at very short timescales (Craver et al. 2014a; 2014b; Wittmann 2011). Importantly, some of these perceptual timekeeping capacities exceed the limitations of the temporal updating system. Consider a well-known study by Stetson et al. (2006). Subjects were asked to press a button and then a flash of light would appear on a screen approximately 35 ms later. In this initial condition, subjects reliably perceived the flash of light as occurring *after* the button press. Next, a delay of 135 ms was inserted between the button press and the flash of light. After subjects adapted to this longer delay, it was removed, and they were once again presented with the light flashing 35 ms after they pressed the button. In this post-adapted condition, despite the stimuli having the same temporal structure as the initial condition, subjects reliably perceived the flash of light as occurring *prior to* the button press.

Notice that the temporal updating system cannot explain the way that these sorts of events are experienced. The temporal updating system can only track the temporal sequence of incoming stimulation. But clearly the timekeeping capacities that are needed to account for these two different experiences are not constrained in this way; they rely on the perceptual system being able to represent the temporal order of distal events in the world.

Examples of perceived temporal order coming apart from the order of sensory stimulation are common in the literature on adult human timekeeping capacities – from the recalibration of temporal order perception within and across modalities (Chen & Vroomen 2013; Vroomen & Keetels 2010; Vroomen et al. 2004), to the flexible recalibration of multisensory simultaneity perception (Mégevand et al. 2013). In all of these cases, the same general explanation can be given for why the perceptual system should show this flexibility. Modality-specific signals from distal events travel at different rates (e.g., light vs. sound), are processed by modality-specific transducers at different rates, and are even transmitted to their respective primary sensory areas at different rates (Vroomen & Keetels 2010). Somehow the perceptual system must have a way of discounting these different asynchronies in the arrival times of sensory signals to produce a coherent picture of how events in the environment are temporally structured. This requires psychological capacities that can represent temporal relations.

At this moment, the critical studies to determine whether animals possess these flexible timekeeping capacities have yet to be conducted, because it is only recently that paradigms for temporal order perception have been modified for animal studies. Nonetheless, if the full range of existing evidence is taken into account, there are good reasons for expecting that animal timekeeping capacities will show a similar sort of flexibility that goes beyond the constraints of the temporal updating system.

First, animals are subject to the same sorts of external and internal factors that create the need to discount asynchronies in the arrival and processing of sensory signals (e.g., the different rates of modality-specific transduction). Second, evidence from hippocampal damage in rats shows that despite losing the ability for sophisticated temporal sensitivity over longer timescales, they nevertheless perform well with timekeeping tasks at very short timescales (suggesting that lack of MTT doesn't imply anything about timekeeping at very short timescales) (Cordes & Meck 2014; Fortin et al. 2002; Yin & Troger 2011). Third, in the few studies that have modified experimental paradigms first used with humans to study temporal order perception in rats (Schormans et al. 2017), macaques (Mayo & Sommer 2013), and starlings (Feenders & Klump 2018), the psychophysical results have been very similar to those found in humans. Fourth, the models of the mechanisms that underpin temporal order perception in adult humans, and that also account for the flexibility of those capacities, are largely modeled off known features of multisensory systems in non-human animals (Cai et al. 2012).

All of this speaks to how plausible it is that animals can represent temporal relations. To properly navigate the world, the perceptual system must interpret the incoming temporal structure of sensory stimulation to properly represent how events in the environment are temporally structured. Although this doesn't amount to the full-fledged ability to reason about moments in time that H&M describe as being the hallmark of the developed temporal reasoning system, it nevertheless shows that animals are not cognitively stuck in time.

Authors' Response

Temporal updating, temporal reasoning, and the domain of time

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Abstract

We focus on three main sets of topics emerging from the commentaries on our target article. First, we discuss several types of animal behavior that commentators cite as evidence against our claim that animals are restricted to temporal updating and cannot engage in temporal reasoning. In doing so, we illustrate further how explanations of behavior in terms of temporal updating work. Second, we respond to commentators' queries about the developmental process through which children acquire a capacity for temporal reasoning and about the relation between our account and accounts drawing similar distinctions in other domains of cognition. Finally, we address some broader theoretical issues arising from the commentaries, concerning in particular the question as to how our account relates to the phenomenology of experience in time, and the question as to whether our dichotomy between temporal reasoning and temporal updating is exhaustive, or whether there might be other forms of cognition or representation related to time not captured by it.

R1. Introduction

Adult human beings can think of the world they live in as being extended in four dimensions, one of which is the temporal one. Doing so involves a rich variety of reasoning abilities, such as (i) the ability to use *tense* to think about what was the case in the past and what will be the case in the future, as well as about what is present, (ii) a grasp of events as happening at *particular times*, each of which only comes round once, and (iii) the ability to represent *temporal order relations* between events, knowledge of which may be crucial to being able to infer what is the case now from information about what happened in the past. In our target article, we contrasted temporal reasoning, thus understood, with a more basic form of cognition, which we call temporal updating. In short, the model of the world that a creature capable only of temporal updating operates with simply lacks a temporal dimension. It concerns the world only ever as it is at present. However, because this model is updated as the creature receives new information and because timing mechanisms can also govern the instantiation of certain elements within the model, a creature equipped only with a temporal updating system can still display behavior that is adapted to how things unfold over time.

Our commentators – even those broadly sympathetic to our account – lay down a number of challenges for us. In this response, we discuss them under three broad headings into which they can be grouped: (1) Explaining animal behavior in time; (2) developmental considerations; and (3) dual systems, representation, and phenomenology. With regard to the first of these, in our target article, we sided with those who claim that animals are incapable of mental time travel, which, within the context of our model, we elaborated as the claim that animals are capable of temporal updating only. In section R2, we return to this claim and extend our account to three forms of animal behavior that we had not discussed in our target article, which commentators cite as evidence against us. In doing so, we also illustrate some more general features of explanations of behavior in terms of temporal updating. We address the second set of issues – that is, developmental ones – in section R3, focusing in particular on commentators' queries about the developmental process through which children acquire a capacity for temporal reasoning and about the relationship between our account and accounts drawing similar distinctions in other domains of cognition. Finally, in section R4, we discuss a set of more general theoretical questions about our account, and in particular two common themes emerging from a number of different commentaries. The first is how our account relates to questions about the phenomenology of experience in time; and the second is whether there might be other forms of cognition or representation related to time that escape our dichotomy between temporal reasoning and temporal updating. In addressing this second theme we return to the issue of animal abilities, and explain some of the reasons underlying our view that animals do not just lack temporal reasoning abilities as we describe them, but that they also do not possess any other, more basic, ways of representing the domain of times.

R2. Explaining animal behavior in time

Before considering some specific types of animal behavior described by commentators as challenges to our account, it may be useful to illustrate with an example the difference between a temporal reasoning explanation and a temporal updating explanation of behavior that unfolds over time. A dog buries a bone and later returns to dig for it. This is a very simple case in which the question can be raised as to whether a creature's behavior demonstrates a capacity for temporal reasoning or whether it can also be explained in a way that credits the creature only with a capacity for temporal updating. On a temporal updating account, the dog initially operates with a model of the world that does not represent a bone as being at the relevant location, but after burying, its model of the world is updated to one that represents a bone as being at that location, and this representation is what explains subsequent digging. A temporal reasoning account of the dog's behavior, by contrast, would explain its digging where it does by crediting it with a past tense belief that it buried the bone there. Note, however, that this explanation is not complete unless the dog is credited with another, general, belief, such as "buried bones stay put." In order to be motivated to dig at the relevant location the dog must not just believe that a bone was buried there in the past; it also needs to have a reason for thinking that the bone is still there now (for discussion, see Bennett 1964).

There are thus two quite different types of explanations of the dog's behavior: Simplifying somewhat,[1] the first appeals to just one *tenseless* belief, and to the idea that the dog acquired that belief in the past and that that belief has persisted over time, whereas the second credits the dog with two beliefs – a past tense belief and a general belief (see also Smith 1982). On a more abstract level, the first explanation is one that appeals to the conditions that determine the instantiation and persistence of a creature's representations over time, rather than appealing to how time itself figures in those representations. Described this way, the buried bone example emerges as just one kind on a much broader spectrum, and the same general type of explanation can also be applied to other, more sophisticated-looking, kinds of behavior. In this section, we will consider three such kinds of behavior described in the commentaries: hummingbirds' foraging behavior (R2.1), delay of gratification in ravens (R2.2), and orangutans' long calls (R2.3).

R2.1. Temporal updating and questions of explanation – the case of foraging behavior

Pan & Carruthers ask how our account would explain the foraging behavior of hummingbirds, which have been shown to be sensitive to the rate at which flowers replenish. As they rightly assume, our account would take it that the birds possess (something like) a timer that gets entrained with the refresh rate of the flower as the bird visits the flower at different intervals after feeding and finds it full again only at some of those intervals. On a temporal updating account, the function of this timer is to make it the case that, at times after feeding that correspond to intervals at which the flower has been found empty, the flower is not represented as full, whereas at times corresponding to intervals at which the flower has been found to be full it is represented as full.

Pan & Carruthers say that they "have no idea how H&M think this is supposed to happen." We think this might be because they don't distinguish clearly enough between two different types of question. Call the first the *mechanism question*. In the case of the dog digging for the bone, which we mentioned at the start of this section, the mechanism question is the question answered by saying that it is simply the tendency of beliefs to persist over time that explains why, even after some time has elapsed, the dog still believes that a specific location contains a buried bone. That is to say, *how it happens* that it has that belief at the relevant time is that it had that belief previously, and that that belief has persisted over time. Similarly, in the case of the hummingbirds, we suggest that the mechanism question is answered simply by saying that particular states of a timer that gets triggered upon feeding from the flower have become associated with a representation of it as empty and others have become associated with a representation of it as full. *How this happens* is explained by the fact that the two types of representations have become associated with the two sets of states of the timer. As a result, the timer being in the former set of states will cause the bird to represent the

[1]We frame the distinction here in terms of two explanations both invoking beliefs, but we want to allow that a temporal updating account could also invoke other types of representational states. This is why we say we are simplifying here.

flower as empty, and the timer being in the latter set of states will cause it to represent the flower as full.

Contrast the mechanism question with another type of question that can take the form "How does it happen?" Going back to our original example of the dog, one can ask why it actually is that the belief about where the bone is buried persists. Why does the dog not simply lose that belief as soon as the bone is out of sight? We might call this the *sensitivity question*, as it concerns the fact that the persistence conditions of the belief about the bone are somehow sensitive to the persistence conditions of the bone itself. We are happy to grant that such a question can be raised for the simple temporal updating account of the dog's behavior that we have given. However, the same question also arises for any account that explains the dog's behavior in terms of a belief, on the part of the dog, that it buried the bone in the relevant location in the past. As we said above, such an explanation is not complete unless the dog is credited with the general belief that buried bones tend to stay put, and there is clearly no reason to ascribe such a belief to the dog unless it is somehow sensitive to the persistence conditions of buried bones.

Similarly, if it is the sensitivity question that **Pan & Carruthers** are after by asking how our account explains the hummingbirds' behavior, the question is how it happens that the birds' timer comes to be entrained with the refresh rate of the flower in the first place. This is indeed an important question, because, for example, such entrainment requires the bird revisiting the flower at different intervals after feeding, which it might be thought to have no reason to do because it has emptied the flower of nectar. Just as with the dog, though, it is wrong to think that our account faces this type of sensitivity question, whereas one that ascribes to the bird representations of the time elapsed since its last visit to the flower doesn't. Pan & Carruthers suggest that the birds have a representation with the content "the flower takes between 10 and 20 clicks [of the interval timer] to replenish." Presumably the idea is that their having this representation, together with a representation of how many clicks ago they visited the flower, is what explains their behavior. But then how does the bird form this representation of how many clicks it takes for the flower to replenish, if not again on the basis of repeated visits to the flower at different intervals after feeding?

Thus, we believe **Pan & Carruthers**'s impression that our account fails to give an explanation of *how it happens* (see also **Kaufmann & Cahen**) may be based on a conflation between two different ways this question may be understood. It is indeed true that the answer to the mechanism question, on its own, does not fully explain animal behavior. Yet it is wrong to think that our account therefore faces an extra explanatory burden, because the sensitivity question, which needs to be answered to provide the full story, is one that alternative accounts of animal behavior face in just the same way.

R2.2. Delay of gratification

Another type of animal behavior that we did not discuss in our target paper is behavior that involves delay of gratification. As **Osvath & Kabadayi** point out, the study of theirs that we used to illustrate experiments on animal tool saving included two conditions in which, among the items the ravens could choose other than the tool, there was also a food reward, albeit one that was smaller than the one obtainable with the tool. Kabadayi and Osvath (2017) argued that the delay after which the birds were given access to the baited apparatus that could be opened with the tool played a significant role in whether they chose the tool or the food reward. The birds were more likely to choose the immediate food reward in a condition in which they had to wait for 15 minutes than one in which they were given immediate access. Osvath & Kabadayi argue that we ignore the role the delay plays in determining the birds' choice, and hence misdescribe the representations underpinning the birds' behavior. We note that, unless we have misunderstood their method, their own results do not force the conclusion that the birds are sensitive to the magnitude of temporal delay per se. The authors described the immediate access condition as one in which the reward in the apparatus was "*spatio*temporally closer" (Kabadayi & Osvath 2017, p. 203, emphasis added) – that is, closer in space as well as time – because the birds walked past and saw the apparatus immediately prior to making their selection, whereas in the 15 minute delay condition they had no such prior perceptual access to the apparatus. The confound of spatial and temporal closeness means that it is not possible to be confident that the birds' behavior was sensitive to the length of the delay.

We will set this point aside because there are numerous other studies that suggest that animals are sensitive to the magnitude of delay periods in delay of gratification procedures (Vanderveldt et al. 2016). Let us assume that **Osvath & Kabadayi** are right that the specific delay at which the ravens get re-introduced to the apparatus has a systematic effect on their choices. What is at issue is whether this means that the ravens must be representing both the current situation and a different, future, situation in which they will be re-introduced to the apparatus, and weighing up how far in the future that situation will be. Ravens, unlike humans, cannot be simply informed about the distance in the future at which an event will happen. Therefore, any difference in their choosing behavior must be based on their prior experiences, when they were either re-introduced to the apparatus almost immediately or only after a 15 minute delay. These different experiences can have an impact on how the apparatus and its associated reward is represented, and in turn influence tool choice. One straightforward possibility, compatible with the idea that delayed rewards are discounted, is that as a result of their learning experiences the birds place less value on the tool when it only yields a reward after delay. Indeed, our account leaves open the possibility that animals could make flexible trade-offs that adjust to the length of delay until reward. In describing our updating explanation of Clayton and Dickinson's studies of scrub jays' memory, we suggested that (something akin to) interval timers may determine the representational contents maintained in the updating system, without the birds being able to represent the time of a previous caching event. Similarly, it is possible that representations of reward magnitude are shaped during learning by the operation of some sort of timing mechanism, without assuming that animals can represent the times at which future rewards will occur. Assuming that some type of timing mechanism is involved here is not controversial. Any account of animal sensitivity to delay in temporal discounting studies must appeal to something along these lines. Our argument is that there is no need to assume that animals actually represent future points in time. Rather, such mechanisms could directly affect representations of the magnitude of rewards.

R2.3. Orangutans' long calls

We believe a third type of animal behavior mentioned in the commentaries, too, can be explained by our account, and this time even without an appeal to timing mechanisms. These are orangutans' long calls, as discussed by **Kaufmann & Cahen** (van Schaik et al. 2013). Van Schaik et al. found that the direction of males' calls emitted in the evening predicted the main direction in which the animals traveled the next day better than chance. Moreover, other orangutans' travel direction was influenced by males' long calls from the previous evening, with females remaining at constant distance from the calling male, whereas other males increased their distance. Kaufmann & Cahen say that "the primary goal of these long calls appears to be to communicate to female orangutans the male's future travel direction" and that the females, as well as other males, "use this information in planning their own travel." This might make it sound as though the conspecifics can determine the direction of the call and then infer from this that the calling male will be found in a certain area in the future. Yet there is actually no reason for thinking that the conspecifics can determine the direction of the males' call in the first place. Rather, as van Schaik et al. (2013, p. 2) themselves point out, the angular difference between the direction of the call and the line connecting the conspecific to the calling male is likely simply to determine the perceived distance from the calling male, without the conspecifics being able to distinguish between the calling male being far away and calling in their direction or closer but calling in a direction away from them. It is therefore more plausible to think that the representation formed upon hearing the call is simply one of how close the calling male is, which is something that could be done within the temporal updating system. If females simply move toward that perceived location if it appears far away, or subordinates move away from it if it appears near, that will be sufficient to yield the observed effect of females staying within earshot of the calling male and subordinates increasing their distance. Yet this would be behavior simply based on a representation of the calling male's perceived location when the call is heard, rather than a representation of its location at some future time.

Obviously, what also needs to be explained is the fact that the calling males do travel in the direction in which they called, and that the conspecifics adjust their own subsequent movements to the perceived location of the call, even though the call was made the previous evening. Van Schaik et al. (2013, p. 8) describe this as being "consistent with the use of some form of episodic memory," but it is unclear why episodic memory should be required to explain these behaviors. Consider van Schaik et al.'s (2013, p. 9) own remark that "the important point is that a male orangutan is maintaining an internally generated directional choice toward a distant target out of current sensory range, over a prolonged time period, despite meandering routes." As this makes clear, the crucial explanatory work is being done by the orangutan *maintaining* this choice over time, that is, forming a representation of a particular distant location as a good location to visit, retaining that representation, and keeping track of its own position relative to that location. We are back to the general type of explanation that we used to account for how the dog, after burying the bone in the garden, can subsequently maintain a representation of its location.

R2.4. Animal behavior in time: Moving the debate forward

We hope that in addressing some of the specific challenges raised by the commentators we have clarified the nature and scope of our account. In each instance, we have suggested that the available evidence does not force the conclusion that animals are capable of temporal reasoning. Of course, our account of these behaviors still leaves a variety of unanswered questions about the precise details of the underpinning mechanisms. However, in our view, mental time travel accounts, when considered properly, also face similar and arguably more difficult questions.

Osvath & Kabadayi's overall criticism is that we are simply rehashing an outdated claim that animals are stuck in time. However, they do seem to agree with us that what animals do is different from humans. At one point, they also describe their view as one according to which animals might "implicitly represent time, without representing time as such." Part of our aim was precisely to try to move forward the debate in this area, which has been dogged by the problem that researchers have resorted to concepts and criteria that are difficult to operationalize. We aim to provide a more specific, empirically tractable characterization of one sense in which animals might be stuck in time. We describe this as their being unable to engage in temporal reasoning, but we also give some operational criteria as to when an organism should be described as only capable of temporal updating. We recognize though that our account of animal behavior is likely to remain controversial. In particular, one general question that might be raised about it is whether there could not also be types of temporal cognition that do not fall neatly into the two categories we have described. This is an issue we will return to in section R4.4.[2]

R3. Developmental considerations

In this section, we turn to issues that commentators raise about our account and human cognitive development. At its most basic, our claim is that being sensitive to temporal features of the world is not the same thing as being able to think about time itself. The idea that there is a distinction between being behaviorally sensitive to a feature of the world and having a proper concept of that feature appears in a wide variety of contexts in developmental psychology. Two challenges that developmental psychologists who make such distinctions typically face are to (1) make clear what the developmental relation is (if any) between the more basic skills and the fully-fledged conceptual grasp of the domain and (2) explain the process of developmental change. As pointed out by commentators (**DeNigris & Brooks**; **Hamamouche**; **Hohenberger**; **Mayhew, Zhang, & Hudson** [**Mayhew et al.**]; **Tillman**), there is considerably more to be said about how our account meets these challenges (for further detail, see McCormack 2015; McCormack & Hoerl 2017).

In what follows, we focus in particular on the following developmental issues: whether the distinction we draw between two different systems can be subsumed under a more general type of distinction also applicable to other domains (R3.1); whether children's early abilities to process duration information provides evidence against the developmental picture we sketched in the target article (R3.2); what factors might underpin the emergence of temporal reasoning abilities in children (R3.3), in particular the development of an ability to represent particular times (R3.4); and what significance the ability to represent particular past times has for humans (R3.5).

[2]As will become clear in that section, we reject Osvath & Kabadayi's suggestion that animals might be described as implicitly representing times not just because of the vagueness of that terminology, but also because of more general consideration about representation.

R3.1. Comparison with other domains of cognition

One key issue raised in a number of commentaries concerns the extent to which our account aligns with claims that have been made regarding other domains of cognition, pointing to a more general type of distinction of which the one between temporal reasoning and temporal updating is only one instance. To give examples from the commentaries: **Redshaw, Bulley, & Suddendorf** link our account with the distinction between skills that do or do not require metarepresentation; **Povinelli, Glorioso, Kuznar, & Pavlic** identify our account as aligning with a distinction between abilities that do or do not require constructing higher-order analogical-based relations; and **DeNigris & Brooks** suggest that our distinction is one between symbolic and non-symbolic representational formats, with the developmental transition understood in terms of Karmiloff-Smith's (1994) notion of representational redescription (see also **Hohenberger**). A more domain-specific parallel is drawn by **Lohse, Sixtus, & Lonnemann**, who argue that developmental changes in numerical cognition can be seen as paralleling those we have described in temporal cognition (see also **DeNigris & Brooks; Roselli**).

We can certainly see the value of considering how our account aligns with more domain-general claims regarding cognitive development. It is also broadly correct to describe the temporal reasoning system as involving a type of higher-order cognition that the updating system does not operate with. However, our account differs from those regarding other domains (such as theory of mind, number, and weight) that the commentators refer to. In those instances, it is typically assumed that infants have some primitive representation of the basic domain, on which the more sophisticated conceptual grasp of the domain builds. For example, in the case of theory of mind, on a number of theoretical approaches, young children are assumed to be operating with some more primitive way of representing the relations between agents and aspects of the world; the developmental achievement is to reach a proper grasp of the nature of the relations in question. The input to the more primitive process is assumed to be perceptually-based in some important sense (such as observation of the interactions between agents and objects), providing an initial "way in" to the domain in question that then provides the foundations for more sophisticated understanding.

By contrast, our view is that the temporal updating system does not provide a similar perceptual "way in" in the case of time, and that the representations of the domain of time with which the temporal reasoning system operates are not simply some sort of more enriched or explicit or redescribed version of representations that the updating system is operating with (see also **Tillman**). Rather, there is an important sense in which the updating system that very young children possess is not operating with temporal representations at all. Indeed, **Oyserman & Dawson** describe the updating system as "atemporal." Similarly, **Melnikoff & Bargh** comment on our account: "To our knowledge, it is the first dual-systems theory to define its systems in terms of possessing versus lacking a single representational dimension."

R3.2. Time as a stimulus dimension vs. time as a framework

Hamamouche argues that our account gets the developmental picture completely wrong: in assuming that infants only have the more primitive updating system, we are ignoring evidence that infants are "well-tuned timers" (see also **Viera & Margolis** for similar points regarding animals). The empirical studies unarguably indicate that very young children possess mechanisms that process temporal duration information. What should be concluded from this? On an alternative developmental picture, one could hold that the representations the updating system deals with are indeed temporal representations of duration, and that the emergence of the reasoning system results from some more explicit or redescribed version of these representations. Such an alternative picture could potentially be seen as aligning with Droit-Volet's description of children as moving from implicit procedural timing to an explicit grasp of the notion of temporal duration (Droit-Volet & Rattat 1999). The difficulty with this picture is that it deals only with what we might call time as a *stimulus dimension* rather than time as a *framework* (McCormack 2015). When time is dealt with as a stimulus dimension, what is processed is the magnitude of stimulus duration; the focus of our paper is with time as a framework in which moments in time have locations relative to each other and relative to the present moment. The latter is what the temporal reasoning system operates with, and our claim is that the updating system does not operate over such a domain because in the updating system other times are not represented at all.

One might argue that it is misleading to describe the temporal updating system as not operating with temporal representations because we are happy to accept that such a system operates with mechanisms that process temporal duration information. Of course, if it is stipulated by definition that the mechanisms that process duration information operate with temporal representations, then, in this sense, the updating system does represent time. However, this only allows for a narrow sense in which duration can be said to be represented. Because the updating system does not represent time as a framework, while duration could be processed as a stimulus property it could not be represented as the amount of time elapsed between two temporal locations (because temporal locations are not represented in the updating system). And this suggests that no proper concept of duration is possible for creatures possessing only the updating system, on the assumption that any conceptual grasp of duration must be grounded in the notion of a period of time between a start point and an end point.

Indeed, these considerations raise the issue of what developmental story should be told about the emergence of the concept of duration (it was this concept that was the focus of Piaget's 1969 work on time). Children do acquire such a concept by the time they are five, as evidenced by their ability to make explicit judgments regarding the lengths of events (Friedman 1990). As yet, we do not know how acquisition of the concept of duration is linked to acquisition of the (other) temporal concepts that the temporal reasoning system operates with (such as concepts of the past and future). We are confident, though, that the reasoning system does not simply deal with representations of time that are somehow more explicit or enriched versions of whatever representations are linked to duration sensitivity in infancy. This is not to say that the temporal reasoning system appears out of the blue. In the target article, we argue that 2- to 3-year-olds may not be full-blown temporal reasoners, but they are not solely reliant on the updating system either. Elsewhere (McCormack 2015; McCormack & Hoerl 1999; 2017), we have argued that children of this age have *event-based* temporal cognition, in which they represent events and event sequences and can think of some events as unalterable (a primitive version of the past tense) and of some as potentially alterable (a primitive version of the future tense). This may be sufficient to underpin some types of future-oriented activity, such as those that involve a sensitivity to the fact that aspects of the environment may change (see **Goulding & Friedman**). However, children of this age will struggle when they have to reason ahead about the temporal order in which future changes will or should happen (Martin-Ordas 2018). There are two key limitations at this stage: children do not represent the times of event occurrences separately from the events themselves, and, accordingly, they do not represent the systematic temporal relations between events (i.e., they do not have linear time). Nevertheless, these event representations provide the basis on which children begin to understand time itself (see also **Mayhew et al.**).

R3.3. Explaining the emergence of temporal reasoning

This still leaves questions about how the temporal reasoning system emerges. A number of the commentators raise the issue of the role of language and enculturation (**DeNigris & Brooks**; **Hohenberger**; **Mayhew et al.**; **Tillman**); this issue is also raised by some commentators when querying why we believe animals do not engage in temporal reasoning (**Gentry & Buckner**; **Montemayor**). The idea that concepts of time are tightly linked to language and/or show substantial cross-cultural differences has a controversial history (Aveni 1990; Gell 1992). We have yet to come across convincing evidence that what we have described as the temporal reasoning system could not be assumed to be universal, and in the target article we suggest that culturally specific constructs may be overlaid on its basic functions. This does not mean, though, that we rule out the possibility that the temporal reasoning system emerges through social interaction. On the contrary, we have a great deal of sympathy for such a view. One approach here is to emphasize a specific role for language itself; as DeNigris & Brooks describe, Nelson (1996) has made a persuasive case for this. In our own writings we have emphasized the role of communication rather than language per se in the acquisition of a linear notion of time. This is because we think that explaining a proper grasp of tense requires making an appeal to distinctive types of shared discourse that allow points in time to be the focus of shared attention with others. This argument is made in detail elsewhere (Hoerl & McCormack 2005), but the general idea is that it is through joint discussion with other people about events at other times that children start to be able to separate out locations in time from the events that occur at those locations and get to grips with the systematic relations between different temporal locations and hence the timeline itself.

Our intuition is that acquisition of temporal concepts is not possible in the absence of such shared discourse about other times, which makes clear, for example, that things in the past were different to how they are right now, or that past events did happen even if they have left no present traces. Indeed, this is part of what motivates us to suspect that animals are not capable of temporal reasoning (in response to **Gentry & Buckner**; **Montemayor**; **Pan & Carruthers**).

R3.4. The self, narratives, and particular times

The picture of the development of the temporal reasoning system that we have just sketched also raises the question of how it links to the developing conception of the self as temporally extended, not least because children's shared discourse about other times typically involves discussions of events in which the child was or will be a participant. We do not have space here to provide a treatment of this issue (see McCormack 2015; McCormack & Hoerl 2001), but in **Oyserman & Dawson**'s commentary, they suggest that the temporal reasoning system is put to use in motivating action not just through a recognition that one is temporally extended, but through a (more sophisticated) recognition that one's future identity is not yet fully fixed. Specifically, they describe the way in which one's current actions are guided by how one envisages the identity of one's future self, using temporal reasoning to steer an appropriate path toward that preferred self.

This seems plausible, and is in line with the idea that temporal reasoning is closely linked to possession of the narrative form (Campbell 1996; McCormack 2015; McCormack & Hoerl 2001). In the case of **Oyserman & Dawson**'s description, the temporal reasoning system serves in a sophisticated way (most likely not present until late childhood/adolescence) to shape the narrative that one wants to have regarding how one's life unfolds. There may, however, be a more developmentally basic link between autobiographical narratives and the temporal reasoning system. Campbell (1996) argued that understanding and using autobiographical narratives (which children properly get to grips with much earlier, around 4 or 5) necessitates a grasp of the unique temporal locations of events – the fact that an event occurred at a specific point in one's life has genuine significance in the context of such narratives. It is this way of representing temporal locations – as unique and unrepeated on a timeline – that is embodied in the temporal reasoning system.

Gentry & Buckner suggest that, contrary to our account, animals may, at least in principle, be capable of thinking about locations in time this way. They argue that there appear to be relatively few genuinely distinctive "landmark" events in animals' lives. Therefore, some animals might be capable of temporal reasoning but their lives may not be populated with sufficiently unique events to construct a structured timeline. While we agree with these commentators that animals have little use for the idea of unrepeated events, it is important to distinguish between an event being unique in the sense of it being unusual (such as moving to a different enclosure) and being unique in the sense of it being represented as happening at a non-recurring time point (an individual occurrence of a repeated event is unique in this sense). Even if an animal did experience a highly salient and rare event, it is difficult to see what use it would make of the fact that this event had occurred at a particular unique time point in its past. Given the nature of animals' lives, this fact does not seem to have any practical significance at all.

R3.5. Temporal reasoning: What is it for?

If animals have no use for the idea that at a certain event took place at a particular time in the past, what makes it the case that this idea can have significance for humans? **Mahr** links this question to the normative dimension of human interaction, arguing that the benefits of temporal reasoning do not lie solely in its role in preparing for the future; rather, "in the psychological and social domains, representing particular past events has benefits in which the particularity and pastness of events matter for their own sake." His suggestion is that grasping the normative dimensions of social interactions (such as one's current obligations) typically hinges on thinking about particular past interactions that explain why the relevant social norm applies. For example, one is entitled to be annoyed if someone fails to keep their promise made yesterday to meet at 5 p.m. today.

One way to think about whether **Mahr** is right about this claim is to consider whether the temporal updating system could in principle be sufficient for operating according to the relevant social norms. Mahr emphasizes the "particularity" of some instances of events, in the sense that they occur in a specific context. We note, though, that the contextual specificity of the implications of particular event occurrences is not what makes them beyond the scope of the more primitive updating system. Rather, Mahr's interesting claim is that appreciation of the pastness of events per se (which the updating system cannot provide) is necessary in order to fully engage with social norms. The case of promises is a good one to focus on, because of the kind of thinking about time that promising seems to involve. If one properly understands what one is doing in making a promise, one is not just committing oneself to delivering on it; rather, one also simultaneously accepts that at a future point in time, others will be entitled to point back to the current moment in time if the promise is not delivered. We therefore agree with Mahr that something like the temporal reasoning system, and not just the updating system, must be involved in properly operating with these sorts of social obligations.

However, such social obligations are not the only examples where appreciating the pastness of certain events matters: this is also true of certain types of complex emotions. For example, regret involves appreciating that there was a moment in time that has now passed at which future events could have unfolded differently but did not (Hoerl & McCormack 2016). This brings us to the issue raised by **Beck & Rafetseder** about the connection between temporal reasoning and counterfactual thought. We agree with their suggestion that developmental research on counterfactual cognition would benefit from a consideration of the "temporal aspects of the demands being made on the child." In fact, we believe that there is an even tighter link between counterfactual and temporal cognition than their commentary explicitly considers. As we mention above, a key achievement associated with the emergence of the temporal reasoning system is the ability to think about locations in time separately from the events that occur in those locations (event-independent thought about time). Elsewhere, we have argued that engaging in counterfactual thought about events in the past (such as the type of counterfactual thought that underpins regret) involves exactly this sort of event-independent thought about time (McCormack 2015; McCormack & Hoerl 2008; 2017). Put simply, the idea is that it involves representing past times as locations in time at which a variety of different events could have unfolded. More than that, when one is engaging in genuinely counterfactual thought about a specific past event, one grasps the fact that at an earlier point in time, the event that is now in the past was once in the future before it unfolded as it did. This is what is at the heart of the idea that *things could have been different*. But if this is the right description of counterfactual thought, then it resembles the sort of temporal perspective-taking that we describe in the paper as being a feature of the temporal reasoning system (i.e., that puts to work the fact that at a different point in time, things that are now in the past were once in the future).[3]

[3]If this analysis is correct, though, one issue that comes to the fore in assessing whether we are correct about animal limitations in temporal cognition is whether animals experience regret (Steiner & Redish 2014; for discussion, see Hoerl & McCormack 2017).

R3.6. The origins of temporal reasoning

We have sketched a developmental picture of the emergence of the temporal reasoning system that is distinctive insofar as we have suggested that the temporal reasoning system does not simply operate with representations that are more explicit or enriched than those over which the updating system operates. In this sense, our account contrasts with some accounts of conceptual development in other domains. But if the reasoning system does not straightforwardly emerge from the updating system, what are its developmental origins? Influenced by Katherine Nelson's work, we suspect that the answer to this question will involve considering how children's emerging ability to represent events and event sequences enables them to engage in discourse with others about past and future events, which allows them to grasp the structure and nature of time itself. That is, we believe that the mature temporal concepts employed within the reasoning system are likely to have social origins. Moreover, it is within a broadly social context that the distinctive purposes for which people use the temporal reasoning system seem to be best illustrated, such as in generating and shaping autobiographical narratives, in evaluating past actions by considering alternative choices that one could have made, and in dealing with social norms and obligations. Research on the developmental origins of temporal concepts is sparse, meaning that these suggestions are speculative. We hope that our account at least provides some impetus for addressing what is currently a surprisingly large gap in the literature on cognitive development.

R4. Dual systems, representation, and phenomenology

In this final section, we pick up on a set of broader theoretical issues emerging from a number of commentaries. The first concerns our characterization of our account as a dual systems account, and the precise grounds on which we draw a distinction between two systems. In subsection R4.1, we emphasize that our account distinguishes between two cognitive systems for dealing with how things unfold over time based on the *content* of the representations maintained, and we contrast this with the idea that the two systems should be distinguished on the basis of the *representational format* of the representations the two systems operate with. We then turn to questions raised by several commentators about how our account relates to the phenomenology of experience in time, discussing first the special place the present has in experience (R4.2) and then the phenomenology of perceptual experiences of dynamic phenomena (R4.3). Finally, we discuss an issue that can be seen to underlie some of the commentaries discussing perceptual phenomenology, but also emerges from some of the other commentaries, which is whether there are ways of representing times that fall outside our dichotomy between temporal updating and temporal reasoning (R4.4).

R4.1. Questions of demarcation: Systems and representational formats

Some commentators suggest ways of extending our account of the temporal updating system and the temporal reasoning system that draw on existing ideas about underlying brain processes. **Nuyens & Griffiths**, in their discussion about the relation between our account and effects of emotion, suggest that the timing mechanisms underpinning some of the workings of the temporal updating system map onto timing processes described in the scalar expectancy theory. **Ueda & Hanakawa** go further and make suggestions about the neural mechanisms underpinning the two systems, and moreover how these may be impaired in certain clinical populations. We do not wish to make any specific claims about the neural substrates of the two systems, although we acknowledge that some researchers may find this frustrating. Moreover, while we describe our account as a dual systems account, we have sought to make it clear that we understand this label quite broadly. For instance, we are happy to agree with **Isham, Ziskin, & Peterson** that our account could also be characterized as a dual process account.

Similarly, our account does not seek to distinguish temporal updating from temporal reasoning on the basis that one involves reasoning (and representations that can underpin the relevant reasoning) and the other doesn't. Indeed, we agree with **Montemayor** that the representations maintained by the temporal updating system could be used to draw inferences (though not necessarily in the particular way he envisages). One basic inference may be illustrated by an example given by **De Brigard & O'Neill**, who note that rodents can switch to taking a longer path in a maze upon learning that a shorter one that they used to take is closed. On our account, learning that the shorter path is closed causes the rat to update its model of the world so that that path is no longer represented as open, and the rat can then infer which of the remaining paths is now the shortest. We see this as an inference the rat can make on the basis of its present, now updated, representation of its environment alone. De Brigard & O'Neill, by contrast, speak of the animal as being "capable of drawing contrastive inferences between outdated and updated representations." If this is to mean that the animal still has a representation, now outdated, of the previously shortest path being open, we see no reason for making such an assumption.

Crucially, our account draws a distinction between two cognitive systems for dealing with how things unfold over time based on the *content* of the representations maintained by those systems. Several commentators, by contrast, suggest variations of or alternatives to our account that involve specific claims about representational *formats*. **Kelly, Prabhakar, & Khemlani** (**Kelly et al.**) suggest that our distinction between temporal updating and temporal reasoning should be seen to map on to two different kinds of iconic representations, which they call "perceptual models" and "event models," respectively. Similarly, **Keven** suggests that one should see the temporal updating system as operating with "snapshot-like" representations that he calls event memories, which are based on automatic perceptual processes.

As we are not committed to any specific claim about the representational format of the representations maintained by the temporal updating system, these other accounts may in principle be compatible with ours, but there are also potential pitfalls if questions of content and questions of format are not clearly distinguished from one another. For instance, as **Kelly et al.** themselves point out, mature thinking about time does not just consist in drawing inferences on the basis of recalled events. It also involves more mundane abilities such as the capacity to simply recount a past sequence of events. It may therefore involve mental states involving quite different representational formats – for example, episodic memories as well as mere beliefs about the time when events happened.

Keven makes a number of claims that we, too, would endorse. For example, he claims that the birds in Clayton and Dickinson's (1998) study need not be able to remember "the actual experience of caching the food items," but might instead "remember in the same way I can remember *where my keys are* without remembering the actual experience of where I put them" (our emphasis). In line with Keven's use of the present tense in drawing this analogy, we similarly believe that the behavior in Clayton and Dickinson's study can be explained by crediting the birds only with a representation that concerns their current environment, though of course one that originates in past experience.

Is there anything more than just a terminological difference between our view and **Keven**'s? The main reason he seems to prefer to frame his view in terms of the idea of "event memories" is that he thinks that information from past experience is retained in a quasi-perceptual format. As he rightly says, our view is not committed to any specific format in which information is retained by the temporal updating system. We regard this as a further, empirical, issue. But even supposing that the representations that make up the model maintained by the updating system are indeed quasi-perceptual, does it follow that the term "event memories" is an apt one? We believe that questions can be asked about both words in that term. With regard to the word "event," consider Keven's description of those representations as "snapshots." Suppose that when I put down my keys, I actually take a photo of them in the location where I put them down, which I then carry around to remind me of their whereabouts. If the only use I subsequently make of this snapshot is to remind me of where my keys are, it seems far from obvious why it should be counted as serving the role of representing *an event*, rather than simply a state of affairs.

Turning to the word "memory," **Keven** exhorts us to "call a memory a memory," and characterizes our description of the model of the world maintained in mere temporal updating as one made up of representations that are at least "memory-like." We believe that this terminology, too, is unhelpful, as the term "memory" is first and foremost a name of a capacity, rather than singling out a particular type of representation. Indeed, on our view, when a creature uses the temporal updating system, there is nothing merely "memory-like" about the capacities that allow it to do so. It clearly uses its memory in so far as it acquires, encodes, and stores information. Thus, on that score, we are more than happy to call memory memory. The reasons for describing the creature as having *a* memory are much less obvious to us.

R4.2. The phenomenology of the present

An existing claim regarding dual systems is that they give rise to what Sloman (1996) calls "simultaneous contradictory beliefs." In section 4 of our target paper, we draw on this idea to connect our dual systems approach with a specific aspect of human adults' everyday picture of time, viz. the fact that it accords a special status to the present moment in time, while also granting that every time has the property of being present when it is that time. Commentators raise a number of questions about this, including: (1) How exactly should this aspect of people's everyday picture of time be characterized (and does it indeed involve a contradiction)? (2) Even if it does involve a contradiction, is this good evidence for the existence of dual systems? (3) How are our claims related to questions about the phenomenology of people's experience of time, which is often held to underpin their everyday picture of time?

The contradiction in people's everyday picture of time, which we suggest might be explained by the existence of the two systems, arises from the idea that time flows or passes. But philosophers

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have given two somewhat different characterizations of this idea. As pointed out by **Miller, Holcombe, & Latham** (**Miller et al.**), as well as **Prosser**, there are ways of spelling out the idea that time flows that do not obviously involve a contradiction. According to *presentism*, only present things exist, and what is called the "flow of time" is simply those things changing. On this view, time itself is an abstraction, rather than a dimension of reality, and moments in time are considered logical constructions (Prior 1972; 1996; for discussion, see Hoerl 2015). The presentist view of the flow of time does not obviously involve a contradiction. A contradiction only arises on what we might call a *moments-based* understanding of the flow of time. Contrary to presentism, this understanding operates with a view of time as a dimension made up of different moments of time. According to it, the flow of time is a change over time in which of these moments is present (or, alternatively, a change that consists in events occupying future, present, and past moments in time in succession).

Does humans' everyday conception of the flow of time correspond more closely to the presentist understanding or to the moments-based understanding of the flow of time? In our target paper, we assumed the latter. In assuming this, we are sympathetic to **Prosser**'s suggestion that people's everyday picture of time is in fact an amalgam of presentism, on the one hand, and *eternalism*, on the other – where the latter is the view that reality is extended in time and that all times are equally real. As Prosser suggests, this might be because the temporal updating system embodies something like a presentist view of reality, whereas the temporal reasoning system embodies an eternalist metaphysics.

Even if this suggestion is along the right lines, it only explains one specific ingredient of people's everyday picture of time. It is focused specifically on the privileged status that our everyday picture of time accords the present moment in time, as one ingredient in the idea that time flows or passes. As implied by what we have just said, and as also pointed out by **Callender**, **Kenward & Pilling**, and **Prosser**, another aspect of the idea of time as flowing or passing is that of a constant change of a certain (perhaps hard to define) type – in Callender's words, the idea that "*future events draw nearer* and *past events recede*" (emphasis in original). We are not claiming to have given an account of the source of this further idea (for one suggested account, see Hoerl 2014b). Yet, even if it is thus limited in its scope, our proposed explanation might help address an important question **Miller et al.** press in their commentary. As they point out, what really needs to be explained is the sense in which it still *seems* to people that the present has an objectively privileged status, even once they have come to the conclusion that it does not. This seeming, Miller et al. say, is different from belief – it is a matter of phenomenology. But how should we think of the type of phenomenology at issue here?

There are clearly aspects of *perceptual phenomenology* linked to time, such as the experience of motion (**Hayman & Huebner**) or sound (**Kenward & Pilling**). We will discuss these in more detail in the next section. For now, it is enough to note that the present moment in time seeming privileged is not a matter of perceptual phenomenology. It is not something that simply figures in perceptual experience alongside, say, motion or sound.

In drawing on Sloman (1996) in our target paper, we aimed to show that there is another, distinct kind of phenomenology – one which dual systems can give rise to. While Sloman frames the point in terms of the idea that dual systems can generate "simultaneous contradictory beliefs," we pointed out that he actually uses the term "belief" in this context in a non-standard way. As **Melnikoff & Bargh** say in their commentary, contradictory beliefs, as such, might also arise in a single system. What we take Sloman to be arguing, rather, is that the existence of dual systems can explain in particular how situations can arise in which a belief-like state can persist – it seeming as though something is true – even though, at the same time, the content of that belief-like state has been dismissed as untrue by the thinker. This is the result of the more basic system still continuing to deliver its verdict, even though this is not endorsed by the more sophisticated system. This would give us a way of understanding how its seeming that the present moment in time has a privileged status can be an aspect of people's phenomenology, even though it is clearly not a matter of perceptual phenomenology.

R4.3. Temporal updating and perceptual experience

Among the commentaries there are some that do focus specifically on perceptual phenomenology – a topic that we did not touch on in our target article. A common theme is that our account takes insufficient account of the dynamic character of perceptual experiences. For example, **Kenward & Pilling** mention the ability to perceive sounds and argue that this ability is evidence that perceptual experience "encompasses happening events rather than just a millisecond snapshot" (compare also **Roselli**). Similarly, **Hayman & Huebner** write: "If a moving object were experienced only as present, each momentary state would feature a static object, with nothing to bind these states together as an experience of ongoing motion." And **Elliott** uses an example from a study with fighting fish conducted by Brecher (1932) to argue that "events separated by time might, given short intervals between their presentations, be combined to form a meaningful … experiential content."

How exactly do these claims bear on our account? On our account, the perception of dynamic phenomena plausibly causes a rapid updating of the model of the world maintained by the temporal updating system. For instance, as a creature watches another creature move, new information about the location of the other creature constantly overrides previous information about its location. This is something our account can clearly accommodate. But the commentators seem to think that our account nevertheless seems to leave out something important about the phenomenology of perceptual experience.

We take it that the authors in question think that we face a dilemma. Either we deny that perceptual experience can encompass more than what **Kenward & Pilling** call a "millisecond snapshot." But that would be to deny the obvious phenomenological truth that we can perceive such things as sounds and movements. Or we allow that perceptual experience can encompass things that happen over an extended period of time. But then perceptual experience might be sufficient, even in animals, to ground representations of different things happening at different times. As Kenward & Pilling put it, we might be right in claiming that animals are incapable of mental time travel and therefore have no way of representing change over longer periods of time. Yet this does not rule out that they are able to do so within the section of the world they are perceptually conscious of. Thus, contrary to what we say, animals' model of the world does contain a temporal dimension, it is just that "their representational timeline may be very short" (Kenward & Pilling).

We have no intention of trying to attack the first horn of this dilemma. Nothing we say is meant to imply any claim to the effect that perceptual experience only encompasses a "millisecond snapshot" (cf. Hoerl 2009; 2013b). However, things are different with the second horn of the dilemma. Does the fact that perceptual experience encompasses things that in fact happen over a period of time imply that it gives rise to representations of different things happening at different times? We are not convinced it does.

Take, for instance, **Elliott**'s example of Brecher's fighting fish. Brecher presented the fish with a tachistoscopic display in which an image of a conspecific repeatedly flashed up briefly in succession. He found that at a frequency of around 30 Hz the fish would attempt to attack the image, even though they would not do so at lower frequencies. Arguably, what this means is that only at 30 Hz or higher frequencies did the fish recognize a conspecific in the display, which in turn means that their visual system must be integrating information over a period of time in which what is in fact a succession of images are flashed up in succession. Yet this does not provide a good reason for thinking that the resulting representation is itself one of succession, or some other form of representation in which times or temporal relations figure. Rather, the relevant representation formed is just that of another fish being present.

We can extract from this a general moral that can also be extended to other examples mentioned in the commentaries. Even if it is necessary for an organism to sample information over time to detect a certain feature of its environment, this does not imply that the resulting representation of that feature is one in which temporal properties or relations figure (for a somewhat related argument, see also Prosser 2016, Ch. 6). This might even be applied to **Kenward & Pilling**'s example of the experience of sound, for instance, which they describe as "inherently a temporal phenomenon." It is true that sounds themselves are temporal phenomena in that they have an onset, an offset, and a duration. But it is ultimately not clear that this marks any deep difference between the way sounds are related to time and the way, for example, colors are. (On this issue, see also Cohen 2010.) Thus, like the latter, they might simply be represented as qualities instantiated at a time.

The same moral also carries over to other considerations not involving perceptual phenomenology. For instance, **Pan & Carruthers** argue that foraging animals must have a representation of time because they can compare the rate of reward at the current location with the average rate experienced at other locations and take this into account in calculating whether they should stay where they are or make the effort to move elsewhere. Clearly, as Pan & Carruthers say, "a rate is a measure of quantity per unit of time." But does that mean that sensitivity to a rate requires an ability to entertain representations in which other times figure?

To adapt an analogy used by Prosser (2016), think of the dial on a car's speedometer. This acts as a representation of a rate, a rate related to the locations the car occupies at different times, but it does not act as a representation of a succession of events happening at different times. Arguably, people also use it in ways that don't need to involve any reasoning about other times, such as when they simply look at the speedometer, notice that they are breaking the speed limit, and take their foot off the gas. In a similar way, we want to suggest that animals may be sensitive to the rate of reward at different locations, but in a way that does not involve any reasoning about different moments in time.

R4.4. Representing space and representing time

In the preceding section, we mentioned **Kenward & Pilling**'s suggestion that animals' model of the world does contain a temporal dimension, but that "their representational timeline may be very short." The general idea here is that there might be ways of representing time that escape our dichotomy between temporal updating and temporal reasoning. A similar idea can be seen to be at work in some of the commentaries that raise issues regarding the relation between temporal and spatial representation.

On our account, space and time are given very disparate treatment by the temporal updating system, which can represent spatial relationships, but ignores altogether that reality also has a temporal dimension. **Callender** questions this, and speaks of "how tightly linked [time and space] are in physics, biology, and psychology." There are clearly a number of ways in which temporal and spatial processing are conceptualized similarly in biology and psychology. Callender mentions the idea that there are "time cells" as well as "place cells" in the brain. Similarly, **De Corte & Wasserman** draw attention to work that has been trying to establish the existence of "temporal maps" in animals. And **Gentry & Buckner** ask why mechanisms for spatial representation that have been demonstrated in animals "could not be bootstrapped to represent an additional temporal dimension as well." To what extent might findings in these areas challenge our view? We will focus in particular on the research on temporal maps.

In a typical backward conditioning study of temporal maps, the animal completes two training phases. In the first, it is repeatedly presented with two different cues (Cue A and Cue B), separated by a time interval. In the second, the animal is presented with a reward, followed soon after by the second cue from the first training phase (Cue B), where the interval between the reward and Cue B is shorter than the interval between Cue A and Cue B in the first training phase. What the research seems to show is that animals integrate the associations between Cue A and Cue B and between the reward and Cue B, including the intervals between them, so that when given Cue A they now expect the reward, despite never having experienced Cue A followed by the reward.

De Corte & Wasserman, who mention this research in their commentary, seem to primarily want to question our characterization of the signature limit that we claim the temporal updating system is subject to. In describing the behavioral implications of a creature operating only with a temporal updating system, we identify as one signature limit of such a system that it cannot deal with situations in which information about changes is received in an order that differs from the one in which these changes happened, and we provide some empirical evidence that children do indeed have problems in situations of this type. We also suggest, though, that even a creature capable only of temporal updating might nevertheless be able to engage in a form of sequential learning, by coming to acquire a routine for updating its model of the world in a particular order.

The type of sequential learning described by **De Corte & Wasserman** is indeed more complex than anything we describe in the target paper. But does it contradict our characterization of the signature processing limit that the temporal updating system is subject to? Note that, while the animal at first learns about two sequences in isolation from each other, it is still the case that it learns about each of those sequences in the order in which that sequence happens. This is different from the kind of case we had in mind when describing the limitations the temporal updating is subject to. These have to do specifically with the fact that the overall outcome of a sequence of changes can sometimes depend on the order in which those changes happen. Now consider a case in which the animal does not directly witness each of the relevant changes in turn, but receives information about their occurrence in an order that does not correspond to the order in which they actually occurred. The only way it can arrive at a correct representation of the overall outcome is if it can reason about temporal order to infer that overall outcome.

As we read them, **De Corte & Wasserman** do not necessarily want to deny that the abilities that have led researchers to credit animals with "temporal maps" can be explained without ascribing to them a capacity for temporal reasoning in our sense. The paradigms used in this research are Pavlovian ones, and they are typically interpreted in associationist terms – the idea being that, when an association between two events is being formed, the temporal relationship between them is also encoded as part of the association between them. This can explain why the animal forms certain expectations at certain times.

However, the use of the term "temporal map" might nevertheless prompt a more general query for our approach. We are making two crucial claims about animals: The first is that they cannot engage in temporal reasoning as we describe it, including mental time travel. The second is that the representations they can entertain are ones from which the dimension of time is simply absent. As can be seen in several places in this response, across a number of different commentaries commentators seem prepared to agree with a version of the first claim, but disagree with the second one (see, e.g., **Hohenberger**; **Osvath & Kabadayi**; **Pan & Carruthers**; **Roselli**). Moreover, the idea that there might be ways of representing things in time that escape our dichotomy of temporal reasoning vs. temporal updating is also a theme in some comments not concerned with animal cognition (see, e.g., **Elliott**; **Hayman & Huebner**; **Kenward & Pilling**; **Viera & Margolis**). We want to end with some remarks on this general issue, addressing in particular the question as to whether it is correct to think of animals' temporal maps as closely analogous to the spatial maps commonly ascribed to them in the literature on animal navigation.

A picture of animal cognition on which animals have basic capacities for temporal representation that closely parallel their capacities for spatial representation has been developed by John Campbell (1994; 2006). On Campbell's account, animals operate with both spatial and temporal frameworks for orienting themselves in their environment, but ones that are crucially different from the kinds of representations of space and time that adult humans can frame. This is because the animal gives causal significance to those frameworks only through its own practical engagement with its environment. In the case of the spatial frameworks used by animals, this implies that, while the animal may be able to represent the direct route from its current location to any other place represented on its cognitive map, "it cannot represent the spatial relations between any two arbitrary places in its environment" (Campbell 1993, p. 87), irrespective of whether it is located at them. The animal's orientation in time is also limited, according to Campbell, in that it is only an orientation with respect to phase, rather than with respect to particular times. Thus, while an animal with a circadian timer might be said to be able to represent an event as happening at noon, on Campbell's account, "it has no use for the distinction between noon on one day and noon on another" (Campbell 1996, p. 118). On Campbell's picture, animals do have temporal frameworks, but these are more primitive and do not allow for times to be represented as unique unrepeating locations on a timeline.

We are happy to go along with Campbell's characterization of the spatial representational abilities of animals. Given this, and given that it is possible to construct a structurally parallel model of their temporal representational abilities, which constitutes something like a halfway house between what we describe as temporal updating and temporal reasoning, respectively, what reasons could there be for being skeptical that such a halfway house exists? We note that in the literature mentioned by **Gentry & Buckner** on ways in which humans recruit spatial representations to think about time, a common claim is that the reverse does not hold – where this is often combined with the claim that time is "abstract" in a way that space is not (Boroditsky 2000; Casasanto & Boroditsky 2008). We think this might point to an important distinction in how talk about temporal maps and spatial maps in animals should be understood.

In the case of spatial maps, there is good reason to think that possession of such a map by an animal involves the ability to represent places in its environment, because the animal uses the map for navigation, that is for actively moving from one place to another. This provides for a concrete sense in which the animal can give significance to the fact that there are places other than the one at which it is located. Yet there is no analogue to this in the case of time. Even if we ascribe to the animal a temporal map such as the ones posited in the literature on backward conditioning, there is nothing the animal can or needs to do to exploit the information encoded in the map other than form the right representations (i.e., first of Cue A, then of the reward, and then of Cue B) at the appropriate moments. But if all an animal can do is generate the right representations at the right moments, then it is not clear that it is useful to describe it as possessing a map of time in the way the term "map" is usually understood, that is, as something that gives the topography of a domain. As we have argued, it could generate the appropriate representation at any given moment without representing other moments in time at all. Thinking of the issue in this way gives the term "mental time travel" its proper import: What is significant about the term is the idea of mentally navigating the temporal domain, that is, making use of a mental map of the structure of relations between points in time. What we are seeking to do is reframe the debate over whether animals can engage in mental time travel as a debate about whether they possess maps of time in this sense.

R5. Conclusion

We are very grateful to all commentators for taking the time to write their commentaries, which have prompted us to both get and be clearer about a number of aspects of the account we are proposing. Given the richness and variety of the commentaries, it has not been possible to provide a detailed discussion of all the points that were raised. Instead, we have focused in particular on looking at ways in which time appears special as a domain of cognition. In all three main sections of this response, we discussed commentators' suggestions to bring ideas already familiar from other domains to bear on our account: for instance, by allowing that animals might be able to implicitly represent the dimension of time, but without representing it as such; by subsuming our account under a broader type of developmental distinction; or by assimilating temporal representation to spatial representation. In each case, while it is certainly helpful to consider such parallels, we suspect that these suggestions do not account sufficiently for the difference between time and other cognitive domains. Specifically, we have argued that while the temporal updating system can explain a range of behaviors that are adapted to how things unfold over time, this does not mean that it provides some primitive way of representing the domain of times.

Conversely, the representations of time that the temporal reasoning system operates with cannot be understood as some sort of more explicit or enriched versions of representations present already in the temporal updating system. Time thus raises its own distinctive issues when it comes to the question as to what it takes to represent it, and how the capacity to do so emerges phylogenetically and ontogenetically.

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[The letters "a" and "r" before author's initials stand for target article and response references, respectively]

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