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Possible evolutionary and developmental mechanisms of mental time travel (and implications for autism)

Melissa J. Allman¹ and Denis Mareschal²

¹Department of Psychology, Michigan State University

²Centre for Brain and Cognitive Sciences, Department of Psychological Sciences, Birkbeck University of London

Abstract

Through an interdisciplinary perspective integrating behavior, neurobiology and evolution, we present a cognitive framework underpinning the development of ‘*time in mind*’ in animals (phylogeny) and humans (ontogeny). We distinguish between conscious processing of events immediately available (in the present) to those that are hypothetical (in the past or future). The former is present in animals and neonates, whereas the latter emerges later in phylogeny and ontogeny (around 4 years of age in humans) and is related to the development of episodic memory (expanded working memory, complex actions, social-cognitive abilities). We suggest that forms of temporal representation that rely upon current bodily sensation across time, space, and action (through embodied interoceptive and motor systems) may be critical causal factors for the evolution of mental time travel.

Introduction

The aim of the current article is to identify potential causal mechanisms at the evolutionary, neurobiological, and developmental levels that may better explain how the mind and brain systems give rise to our subjective sense of time. Although mammals and corvids show some signs of mental time travel, (as evidenced, for example, by episodic memory or forward planning; see [1, 2, 3, 4] for a greater discussion of non-human animal abilities), humans have functionally superior mental abilities that allow them to consciously think and act upon events (either intentionally or unintentionally) in the past and future [1]. We will suggest that this ability probably had some evolutionary advantage, perhaps through its relation to the increase in the size of hunter-gather social networks (and cooperative hunting practices) that became connected over vast distances, thereby placing demands for social-cognitive abilities and past or future thinking—beyond the ‘*here-and-now*’ [5]. We will also suggest that temporal (e.g., duration) estimations may be based on interoceptive information

Address all correspondence to: Dr. MJ Allman, 108 Giltner Hall, 293 Farm Lane, Michigan State University, Department of Psychology, East Lansing, MI 48824, USA. mjallman@msu.edu.

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that extends beyond the temporal limits of working memory, thereby engendering a sense of extended time and self [6]. This has also been proposed as necessary for the emergence of episodic memory [7], itself a requirement for thinking about hypothetical events in the future (see Figure 1).

The psychological present: working memory and attention

The “psychological” or “specious” present has a long history in the study of human psychology and refers to the conscious state of “now”. The existence of an approximately 3 second [8] or even 5 to 8 second correspondence window that situates events within the conscious state of “now” has been contested [9], with the assertion that it is instead of no fixed duration, but rather, is based on the duration of an experiential process and the capacity to apprehend information into a unified group that has not yet been stored in memory [10]. The notion of the subjective present as a mental platform, with a limited temporal boundary, that processes some ‘online’ integration of current events over a brief period of objective time in consciousness (via controlled attention) resonates well with notions of short-term memory, working memory and the episodic buffer [11]. The idea here is that discrete experiential platforms, “experiential moments”, or phenomenal ‘presents’, are integrated in dynamic succession such that time “flows” between these platforms and is not experienced as static.

Sensitivity to the temporal qualities of stimulus events is observed in many species, chiefly in the ability to learn conditional relations between events. Studies of Pavlovian and operant conditioning in animals (using trace eyeblink conditioning and peak-interval procedures respectively) reveal a ‘ramping up’ over many trials of the conditioned or operant response to a peak amplitude around the ‘expected’ criterion (CS-US/PI) interval duration. Animals are also capable of linking the passage of time with ongoing behavior, and may even use actions to parse or discriminate an interval [12]. These interval-timing-based responses may appear to extend for durations beyond the breadth of the psychological present. However, most interval timing models (e.g., pacemaker or cortical oscillations models) require the ‘onset’ (or re-setting) of timing mechanisms during the initiation of the to-be-timed stimulus [13, 14]. This (re)-setting is cued or triggered by the target stimulus being (or having been) present in the immediate “now”. Thus, although the timing may extend for durations beyond the breadth of the psychological present, it is nevertheless bound by internal or external cues (or states) that are experienced in the immediate “now”. For instance, corvids tend to choose to cache an alternate vs. a recently consumed food; thus, their apparent mental time travel behavior appears bound by current internal states (e.g., sensory-specific satiety; but see [15]). Under this type of conception, any type of processing in the conscious (online) “now” can be defined as a form of phenomenal consciousness, so it is perhaps more useful to conceive of the “now” as an operation or experiential process such that the flow of subjective time is mediated by the succession of thoughts [16, 17]. That is, some forms of ‘time in mind’, notably interval timing and rhythm perception and production, appear to correspond to the conscious processing of events that correspond to external cues or internal states that are currently impinging on the individual. They are therefore deemed to occur in the present or “now”.

Interval timing and working memory both require information (e.g., a stimulus duration) to be held in consciousness, and can be distorted by attention and cognitive load manipulations [18]. Many of the most successful interval timing models (see French et al, this issue, for a review of interval timing models) functionally incorporate a working memory component through reference to attention, or other filtering and decision-making processes. Interval timing and working memory also rely upon the same neural representation of a given stimulus (e.g., cortical oscillations in the frontal cortex and detection by striatal spiny neurons [19]). A primary ‘first-step’ for the central nervous system is to make sense of information with respect to its spatial and temporal qualities to produce motor actions coordinated to events in the environment. Indeed, the representation of space and time appears to be, to some extent, mutually conserved (e.g., the spatial-temporal role of the hippocampus; the ‘mental number-line’), and may even share a common magnitude metric from early in infancy (see [20]).

In adults, the progression of time is represented spatially such that short temporal durations and past events (even those elicited through tenses), are associated with left space, and long temporal durations and future events, are associated with right space [21]. However, the a mental time line does not appear to emerge until late childhood (8 to 10 years of age) and so does not appear to be a primitive quality of temporal representation [22]. When temporal magnitude estimations are retrospective, adults (and other non-human animals) appear to estimate the duration based on the nature of the events that filled the interval (i.e., their number, and estimated duration). Thus, one (positively) filled event might seem to fly by in the moment, but seem longer in retrospect; while an unfilled event may seem to drag in the moment, but seem shorter in retrospect. It has been suggested that the adequate processing of the spatial, temporal and numerical qualities of environmental stimuli is evolutionarily adaptive. A spatial quality to time may facilitate the ability to sense time continuously over a protracted interval. Given that ancestral hunter-gathers needed to communicate over vast distances [5], it can be speculated that the communication of distance information could have involved some form of temporal magnitude estimation (e.g., *duration* of a trip, *number* of provisions). There is growing evidence for the existence of a spatial quality to time and number processing at the neurobiological level [23]. Moreover, in humans, counting and symbolic number representation also have temporal (i.e., 1 per sec), and spatial phenomenological correspondence.

In addition to a perceptual sensitivity for duration [24, 25] infants are born with sensitivity to external rhythm [26, 27]. From 6 to 12 months of age, there are quantifiable gains in temporal sensitivity at the behavioral and neural levels [28, 29]. This coincides with: (1) the child’s growing sensitivity to the temporal hierarchical structure of events using primitive goal detection systems that can parse dynamic action—presumed to be phenomenologically related to detecting the intentions and goals of others [30], and (2) learning to walk (i.e., an ability to willfully and with intention act in their environment). Moreover, within the first year of life, social parent-infant interactions reveal different types of temporal patterning (in optimal arrangements [31]), that allow an infant to adjust their expectations and behavior to changes in the parent’s tempo. These interactions are disrupted in infants who later receive a diagnosis of autism [32]. Older children with autism also tend

to reveal impairments in causal learning between component actions, and conceptual organization of action knowledge [33]. In sum, during the first year of life perceptual and cognitive development is largely constrained to events in the “here-and-now”, and those on relatively short-scale timescales. At the neurobiological level, stereotypical behaviors and interval (and beat-based) timing are sub-served by similar circuits (e.g., cortico-striatal circuits; action on the D2 receptor) [34, 35]. Disruptions to these circuits create problems in sequencing components of action and complex behavior. Thus producing stereotyped, repetitive thought and action (in addition to impulsivity; see [36]). This appears to be typical in infancy [37] but becomes atypical if it extends into childhood (as in some developmental and intellectual disabilities, including autism; where treatment seeks to reduce them).

While animals are capable of some forms of rhythm production, they are not believed to be capable of beat extraction, or synchronizing their motor activity to an external beat (but see [38, 39]). This type of culturally universal ability in humans is probably related to our social evolution. For example, dancing is anthropologically related to story telling; the relaying of past episodic experience and future predictions, which places demands upon mental time travel abilities. Rhythm is a fundamental structure for the developing mind (psychic performance), and allows an individual to gain increasing control over actions. Intriguingly, individuals with Parkinson’s disease (striatal and dopaminergic impairments) often experience difficulty initiating and sustaining coordinated motion with static, but not dynamic, stimuli (e.g., their walking is facilitated if a chalk line is drawn in front of them as they walk, rather than pre-drawn). Similarly, people who stutter may not do so when they sing (even a cappella), such that the (external or imagined) rhythm of the song facilitates vocal initiation patterns through activation of alternate, but related neural pathways [40, 41]. In short, the idea that we are advancing here is that temporal, spatial and action processing are inextricably linked. They form the basis of the more advanced human-like abilities, possibly arising from an increased reliance on working memory and social-cognitive demands for mental time travel.

The psychological past and future: Episodic memory

Baddeley [42] proposed that a consequence of greater working memory capacity would be increased processing (reflection, comparison) of past experiences, and more successful future actions. The episodic buffer, a new component integrated into the traditional working memory model [43], is a system whose role is to integrate multi-modal information (e.g., from current sensory-motor systems, and long term memory) into a unified episodic representation. Within this account, common constructive cognitive processes support episodic memory and episodic future thinking. This might “allow an individual to actively choose a future action or create an alternative action, rather than simply choosing the highest path of probable success” [5]. Further, natural selection likely favored voluntary access (working memory) to long-term memories pertaining to the current environment, such that the consequences of intended future actions could be pre-conceived without need for physical risk [44]. A sense of agency is an important precondition for higher level mentalizing abilities, including episodic memory. On the grounds of parsimony it is reasonable to suppose that basic associative mechanisms of learning and memory, reward

prediction, and timing and time perception, play some role in temporal estimation processes when the contents of phenomenological consciousness include the recall of hypothetical episodic events (i.e., in the imagined past or future), in the episodic buffer and consciousness.

There is an experiential ‘flavor’ or quality to recalled (or imagined) episodic events (autoneosis, [7]) and an awareness of the subjective time in which events occurred. Arguably, this is perhaps most salient if the temporal representation includes an embodied (spatial, emotional) quality. A possible causal mechanism of how action, spatial and temporal processing form the basis for more advanced human-like mental time abilities, is possibly related to sequence learning (learning chains of events) and embodied cognition—the idea that interoceptive and feeling states of the body serve as a basis for the temporal code [45]. “The perception of time would thereafter be embodied; the bodily self, the continuous input from the body is the functional anchor of phenomenal experience and the mental self” [●●6] This may provide the basis of the three concepts essential for episodic memory—sense of self, autoeotic awareness, and subjectively sensed time [7].

Evolutionarily speaking, the need for episodic memory is likely to be related to the ability for future thinking by incorporating “known elements arranged in unique ways that could have occurred in the past but did not, and may occur in the future but might not... [which] provide raw material from which to construct and innovate possible future scenarios” [5]. The development of episodic memory has been argued to separate out modern human and contemporary hunter-gatherers from Neanderthals as growing social groups and the division of labor demanded ever-growing social–cognitive abilities (e.g., theory of mind, following rules; [5]). There is empirical evidence of rudimentary episodic memory and future planning in food caching corvids who are able to keep track of different food items’ relative rate of decay [46]. Despite the capability of a corvid to recall and reason about the what-where-when of previous episodic events [47] it does not follow that it is necessary to experientially ‘replay’ in consciousness previous caching episodes [1]. Animals have also been shown to pass Tulving’s [48] modified ‘Spoon test’ by selecting and retaining an item for a temporally distant event (future), based upon some prior episodic experience (past)[●●49].

In humans, episodic memory is: evolutionarily and ontogenically relatively late developing (i.e., heavily recruiting prefrontal cortices); particularly vulnerable to neuronal dysfunction (and usually one of the first type of memories to be lost in dementia); and distributed throughout the brain, in accordance with cortical evolution, in cortical and subcortical networks (frontal, overlapping and extending those recruited for other forms of memory). Deficits in episodic memory (and a disorientation of the self in time and space) are characteristic of the majority of clinical neurological patients, and may be induced by a variety of psychoactive substances and perturbations in brain chemistry (e.g., neuropsychiatric disorders and psychosis). People with neuropsychiatric disorders (e.g., schizophrenia, global amnesia) have been argued to lack episodic foresight and have distorted cognitive temporal representations of events with respect to their occurrence in the past, present and future, which manifests in maladaptive thoughts and behavior [●50, 51].

We propose that the emergence of theory of mind and Piagetian conservation requires mental time travel (episodic hind/foresight) by stepping outside the “here-and-now” (and not being bound by the present). Empirical findings reveal that around 4 years of age, children become able to learn flexible temporal casual relations between events in the past, present and future [52]; and that the understanding of past and future develop in parallel [53]. Understanding deliberate practice (requiring episodic foresight and social-observational learning) and conservation (mentally reversing an action) emerges slightly later (around 6 years). Considerably less is known about the development of action processing during the preschool years, which is surprising as this corresponds to the time in development when children become adept at integrating information obtained from observations of others into internally and externally specified goals [54, 55]. With respect to interval timing, there are developmental improvements in sensitivity and precision throughout infancy [28, 29] and childhood (see Droit-Volet this issue). In adulthood, ‘mature’ ways of thinking and acting may be characterized by an increased (most likely conscious) consideration of hypothetical events that may or may not occur in the future (including the intentions of others), and which may or may not draw upon past recollection of episodic (or semantic) memories (in consciousness). Relatedly, there is some evidence that in old age, thoughts of the future are attenuated and replaced with increased conscious recollections of past episodic events [56].

There is a collection of recent findings suggesting that children with autism may have difficulty with aspects of mental time travel, and a wealth of evidence that affected children do not reveal a recall bias for personally experienced events; have poor episodic memory; and have impaired mentalizing (e.g., see [57, 58, 59, 60, 61]).

Aberrant/stereotyped behaviors have even been posited to be self-generated reassurances of the continued existence of self in time [e.g., see 62], and some of these may be caused, in part, by fundamentally altered sensory-motor and vestibular/embodied processing. Indeed, sensory hypo/hypersensitivity has recently been recognized for diagnosis of autism spectrum disorder, and may possibly be related to pathophysiological differences in interval timing [63], particularly for relatively longer durations, and thus may account for the atypical sense of self in autism [64]. It is not difficult to appreciate that (based on our tendency to base our current actions and thoughts on past and future events), to a child who is ‘lost in time’ (as may be in autism; see [65]), human behavior might be highly unpredictable, and that a preference for engaging in activities with animals (who live in the “now”) and so-called ‘male’ systemizing interests (e.g., machines, moving parts; that are predictable, have low temporal information processing/mental time travel demands) might predominate [66]. Thus, contemporary theories of autism referencing Theory of Mind, weak central coherence, executive function, extreme male brain, or even prediction (e.g., [67]) can all be accommodated within the proposed framework. The argument here is that the emergence of mental time travel (episodic memory, future thinking) is a required building block for social-cognitive mentalizing abilities, and may relate to other properties of interval timing [68, 69]. Finally, *Von Economo neurons* (large spindle-shaped cells in anterior cingulate and anterior insular) may be the neurobiological path toward mental time travel in humans [70], linking

an embodied sense of self in time, with social cognition that demands rapid mental time travel abilities.

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References

- Papers published within the period of review, and of particular interest, have been highlighted as: ● of special interest ●● of outstanding interest
- [1]. Suddendorf T, Corballis MC. The evolution of foresight: What is mental time travel and is it unique to humans? *Behav Brain Sci.* 2007; 30:299–351. [PubMed: 17963565]
 - [2]. Zentall TR. Mental time travel in animals: A challenging question. *Behav Process.* 2006; 72:173–183.
 - [3]. Thom JM, Clayton NS. Route-planning and the comparative study of future thinking. *Front Psychol.* 2015; 6:144. doi:10.3389/fpsyg.2015.00144. [PubMed: 25717315]
 - [4]. Suddendorf T, Addis DR, Corballis MC. Mental time travel and the shaping of the human mind. *Philos Trans R Soc Lond B Biol Sci.* 2009; 364:1317–1324. [PubMed: 19528013]
 - [5]. Coolidge F, Wynn T. The role of episodic memory and autonoetic thought in upper Paleolithic life. *PaleoAnthropology.* 2008:212–217.
 - [6]. Wittman M. Modulations of the experience of self and time. *Conscious Cogn.* 2015; 38:172–181. [PubMed: 26121958] ●● This review highlights the correspondence between interoceptive and emotional states and the subjective sense of time; and how this is revealed through altered states of consciousness, psychoactive drugs and psychiatric/psychological conditions.
 - [7]. Tulving E. Episodic memory: from mind to brain. *Ann Rev Psychol.* 2002; 53:1–25. [PubMed: 11752477]
 - [8]. Poppel E. Pre-semantically defined temporal windows for cognitive processing. *Philos Trans R Soc Lond B Biol Sci.* 2009; 364:1887–1896. [PubMed: 19487191]
 - [9]. Fraisse P. *The Psychology of Time.* Harper and Row; 1963.
 - [10]. Fraisse P. Perception and estimation of time. *Ann Rev Psychol.* 1984; 35:1–36. [PubMed: 6367623]
 - [11]. Baddeley A. The episodic buffer: a new component of working memory? *Trends Cogn Sci.* 2000; 4:417–423. [PubMed: 11058819]
 - [12]. Killen P, Fetterman JG. A behavioral theory of timing. *Psychol Rev.* 1988; 95:274–295. [PubMed: 3375401]
 - [13]. Matell MS, Meck WH. Neuropsychological mechanisms of interval timing behavior. *BioEssays.* 2000; 22:94–103. [PubMed: 10649295]
 - [14]. French RM, Addyman C, Mareschal D, Thomas E. GAMIT: A fading-Gaussian activation model of interval-time — unifying prospective and retrospective time estimation. *Timing Time Percept Rev.* 2015; 1(2) doi: 10.1163/24054496_001_01_s002.
 - [15]. Cheke LG, Clayton NS. Eurasian jays (*Garrulus glandarius*) overcome their desires to anticipate two distinct future needs and plan for them appropriately. *Bio Lett.* 2012; 8:171–175. [PubMed: 22048890]
 - [16]. Fingelkurts AA, Fingelkurts AA. Present moment, past, and future: mental kaleidoscope. *Front Psychol.* 2014; 5:395. [PubMed: 24822050]
 - [17]. Fingelkurts AA, Fingelkurts AA, Neves CFH. Natural world physical, brain operational, and mind phenomenal space-time. *Phys Life Rev.* 2010; 7:195–249. [PubMed: 20417160]

- [18]. Droit-Volet S, Fayolle S, Lamotte M, Gil S. Time, emotion and the embodiment of timing. *Timing Time Percept.* 2013; 1(1):99–126.
- [19]. Gu B-M, van Rijn H, Meck WH. Oscillatory multiplexing of neural population codes for interval timing and working memory. *Neurosci Biobehav Rev.* 2015; 48:160–185. [PubMed: 25454354]
- [20]. Allman MJ, Pelphrey KA, Meck WH. Developmental neuroscience of time and number: implication for neurodevelopmental disabilities. *Front Integr Neurosci.* 2012; 6:7. [PubMed: 22408612]
- [21]. Bonato M, Zorzi M, Umiltà C. When time is space: evidence for a mental time line. *Neurosci Biobehav Rev.* 2012; 36:2257–2273. [PubMed: 22935777]
- [22]. Droit-Volet S, Coull J. The developmental emergence of the mental time-line: spatial and numerical distortion of time judgment. *PLoS ONE.* 2015; 10(7):e0130465. [PubMed: 26135743]
- [23]. Dallal NL, Yin B, Nekovářová T, Stuchlík A, Meck WH. Impact of vestibular lesions on allocentric navigation and interval timing: the role of self-initiated motion in spatial-temporal integration. *Timing Time Percept.* 2015; 3:269–305.
- [24]. Colombo J, Richman WA. Infant timekeeping: attention and temporal estimation in 4-month-olds. *Psychol Sci.* 2002; 13:475–479. [PubMed: 12219817]
- [25]. Winkler I, Háden GP, Ladinig O, Sziller I, Honing H. Newborn infants detect the beat in music. *Proc Nat Acad Sci USA.* 2009; 106:2468–2471. [PubMed: 19171894]
- [26]. Phillips-Silver J, Trainor LJ. Feeling the beat: movement influences infants' rhythm perception. *Science.* 2005; 308:1430. [PubMed: 15933193]
- [27]. Zentner M, Eerola T. Rhythmic engagement with music in infancy. *Proc Nat Acad Sci USA.* 2010; 107:5768–5773. [PubMed: 20231438]
- [28]. Addyman C, Rocha S, Mareschal D. Mapping the origins of time: scalar errors in infant time estimation. *Dev Psychol.* 2014; 50:2030–2035. [PubMed: 24979472] ●● This study revealed that like adults, infants' time estimations become more variable as the time interval increases (3- to 5-s). This is a hallmark quality of time perception (scalar property), and is revealed by 4 months of age.
- [29]. Brannon EM, Suanda S, Libertus K. Temporal discrimination increases in precision over development and parallels the development of numerosity discrimination. *Dev Sci.* 2007; 10:770–777. [PubMed: 17973794]
- [30]. Baldwin DA, Baird JA, Saylor MM, Clark MA. Infants parse dynamic action. *Child Dev.* 2001; 72:708–717. [PubMed: 11405577]
- [31]. Stern, DN.; Beebe, B.; Jaffe, J.; Bennet, SL. The infant's stimulus world during social interaction: a study of caregiver behaviors with particular reference to repetition and timing. In: Shaffer, HR., editor. *Studies of mother-infant interaction.* Academic Press; 1977. p. 177-204.
- [32]. Wimpory, D. A social timing model of autism, informed by typical development. In: Vatakis, A.; Allman, MJ., editors. *Time distortions in mind: temporal processing in clinical populations.* Brill; 2015. p. 57-92.
- [33]. Zalla T, Labruyere N, Georgieff N. Goal-directed action representation in autism. *J Autism Dev Disord.* 2006; 36:527–540. [PubMed: 16568354]
- [34]. Garner JP, Mason GJ. Relationship between cage stereotypies and behavioral disinhibition in lab laboratory rodents. *Behav Brain Res.* 136:83–92. [PubMed: 12385793]
- [35]. Gu BM, Cheng RK, Yin B, Meck WH. Quinpirole-induced sensitization to noisy/sparse periodic input: temporal synchronization as a model of obsessive-compulsive disorder. *Neuroscience.* 2011; 17:143–150. [PubMed: 21284954]
- [36]. Allman MJ, Meck WH. Pathophysiological distortions in time perception and timed performance. *Brain.* 2012; 135:656–677. [PubMed: 21921020] ● This review is focused on psychiatric/psychological and neurological disorders. It discusses the relative functioning of (various stages

of) interval timing in these populations, and how timing differences appear to influence aspects of the behavioral phenotypes.

- [37]. Thelen E. Rhythmical stereotypies in normal human infants. *Anim Behav.* 1979; 27:699–715. [PubMed: 556122]
- [38]. Patel AD, Iversen JR, Bregman MR, Schulz I. Experimental evidence for synchronization to a musical beat in a nonhuman animal. *Curr Biol.* 2009; 19:827–830. [PubMed: 19409790]
- [39]. Hattori Y, Tomonaga M, Matsuzawa T. Spontaneous synchronized tapping to an auditory rhythm in a chimpanzee. *Sci Rep.* 2013; 3:1566. [PubMed: 23535698]
- [40]. Alm PA. Stuttering and the basal ganglia circuits: a critical review of possible relations. *J Commun Disord.* 2004; 37:325–369. [PubMed: 15159193]
- [41]. Wieland EA, McAuley JD, Dilley LC, Chang S-E. Evidence for a rhythm perception deficit in children who stutter. *Brain Lang.* 2015; 144:26–34. [PubMed: 25880903]
- [42]. Baddeley A. The episodic buffer: a new component of working memory? *Trends Cogn Sci.* 2000; 4:417–423. [PubMed: 11058819]
- [43]. Baddeley, AD.; Hitch, GJ. Working memory. In: Bower, GA., editor. *The Psychology of Learning and Motivation.* Academic Press; 1974. p. 47-89.
- [44]. Shepard, R. The genetic basis of human scientific knowledge. In: Bock, G.; Cardew, G., editors. *Characterizing Human Psychological Adaptations.* Wiley & Sons; 1997. p. 4-13.
- [45]. Kranjec A, Chatterjee A. Are temporal concepts embodied? a challenge for cognitive neuroscience. *Front Psychol.* 2010; 1:240. [PubMed: 21833293]
- [46]. Clayton NS, Yu KS, Dickinson A. Interacting cache memories: evidence for flexible memory use by western scrub-jays (*Aphelocoma californica*). *J Exp Psychol Anim Behav Process.* 2003; 29:14–22. [PubMed: 12561130]
- [47]. Clayton NS, Bussey TJ, Dickinson A. Can animals recall the past and plan for the future? *Nat Rev Neurosci.* 2003; 4:685–691. [PubMed: 12894243]
- [48]. Tulving, E. Episodic memory and autonoesis: uniquely human. In: Terrace, H.; Metcalfe, J., editors. *The Missing Link in Cognition.* Oxford University Press; 2005. p. 4-56.
- [49].
- Scarf D, Smith C, Stuart M. A spoon full of studies helps the comparison go down: a comparative analysis of Tulving's spoon test. *Front Psych.* 2014; 5:893. ●●This review is focused on mental time travel, both thinking of an event in the past, and pre-experiencing an event in the future. It includes studies examining this in both non-human animals and preschool children.
- [50].
- Cole SN, Catriona MM, Barak O, Pauly-Takacs K, Conway MA. Amnesia and future thinking: exploring the role of memory in the quantity and quality of episodic future thoughts. *Brit J Clinical Psychol.* 2015 doi: 10.1111/bjc.12094. [Epub ahead of print]. ●This is a clinical case study of a person with amnesia (and age-matched controls) examining past and future episodic memory. An impairment in episodic memory is associated with reduced and outdated future episodic memory in this patient.
- [51]. Allman, MJ.; Yin, B.; Meck, WH. Time in the psychopathological mind. In: Arstila, V.; Lloyd, D., editors. *Subjective Time: The Philosophy, Psychology, and Neuroscience of Temporality.* MIT Press; 2014. p. 637-54.
- [52]. Lohse K, Kalitaschke T, Ruthmann K, Rakoczy H. The development of reasoning about the temporal and causal relations among past, present, and future events. *J Exp Child Psychol.* 2015; 138:54–70. [PubMed: 26037402]
- [53].
- Cuevas K, Rajan V, Morasch KC, Bell MA. Episodic memory and future thinking during early childhood: linking the past and future. *Dev Psychobiol.* 2015; 57:552–565. [PubMed: 25864990]
- This study examines the concurrent emergence of past and future thinking between 3- and 4

years of age. There were no significant age-related differences in children's ability to utilize episodic future thinking, and episodic memory was superior to future episodic memory.

- [54]. Freier L, Cooper RP, Mareschal D. The planning and execution of natural sequential actions in the preschool years. *Cognition*. 2015; 144:58–66. [PubMed: 26232585]
- [55]. Freier L, Cooper RP, Mareschal D. Preschool children's control of action outcomes. *Dev Sci*. 2015 doi: 10.1111/desc.12354.
- [56]. Bernstein D, Rubin DC, Salgado S. The frequency of involuntary autobiographical memories and future thoughts in relation to daydreaming, emotional distress and age. *Conscious Cogn*. 2015; 36:352–372. [PubMed: 26241025]
- [57]. Terrett G, Rendell PG, Raponi-Saunders S, Henry JD, Bailey PE, Altgassen M. Episodic future thinking in children with autism spectrum disorder. *J Autism Dev Disord*. 2013; 43:2558–68. [PubMed: 23504377]
- [58]. Lind SE, Bowler DM, Raber J. Spatial navigation, episodic memory, episodic future thinking, and theory of mind in children with autism spectrum disorder: evidence for impairments in mental simulation? *Front Psychol*. 2014; 5:1411. [PubMed: 25538661] ● This study examined several (related) cognitive abilities and reports selective impairments in past and future episodic memory, and spatial navigation (itself somewhat predictive of repetitive behaviors). Findings are interpreted in the context of self-projection and scene construction.
- [59]. Maister L, Plaisted-Grant KC. Time perception and its relationship to memory in autism spectrum conditions. *Dev Sci*. 2011; 14:1311–1322. [PubMed: 22010891]
- [60]. Lind SE. Memory and the self in autism: a review and theoretical framework. *Autism*. 2010; 14:430–456. [PubMed: 20671017]
- [61]. Sperduti M, Pieron M, Leboyer M, Zalla T. Altered pre-reflective sense of agency in autism spectrum disorders as revealed by reduced intentional binding. *J Autism Dev Disord*. 2014; 44:343–352. [PubMed: 23881092]
- [62]. Skirrow P, Jackson P, Perry E, Hare DJ. I collect therefore I am—autonoetic consciousness and hoarding in Asperger syndrome. *Clin Psychol Psychother*. 2015; 22:278–284. [PubMed: 24615808]
- [63]. Allman, MJ.; Falter, CM. Timing processes in autism spectrum disorder. In: Vatakis, A.; Allman, MJ., editors. *Time Distortions in Mind – Temporal Processing in Clinical Populations*. Brill; 2015. p. 37-56.
- [64]. Uddin LQ. The self in autism: an emerging view from neuroimaging. *NeuroCase*. 2011; 17:201–208. [PubMed: 21207316]
- [65]. Allman, MJ.; DeLeon, IG. 'No time like the present': time perception in autism. In: Giordano, AC.; Lombardi, VA., editors. *Causes and Risks for Autism*. Nova Science Publishers; 2009. p. 65-76.
- [66]. Grandin, T.; Johnson, C. *Animals In Translation: Using The Mysteries Of Autism To Decode Animal Behavior*. Harvest Books; 2005.
- [67]. Sinha P, Kjelgaard MM, Gandhi TK, Tsourides K, Cardinaux AL, Pantazis D, Diamond SP, Held RM. Autism as a disorder of prediction. *Proc Nat Acad Sci USA*. 2014; 11:15220–15225. [PubMed: 25288765]
- [68]. Cheng RK, Tipples J, Narayanan NS, Meck WH. Clock speed as a window into dopaminergic control of emotion and time perception. *Timing Time Percept*. 2016 in press.
- [69]. Allman MJ, Teki S, Griffiths TD, Meck WH. Properties of the internal clock: first- and second-order principles of subjective time. *Ann Rev Psychol*. 2014; 65:743–771. [PubMed: 24050187]
- [70]. Allman JM, Watson KK, Tetreault NA, Hakeem AY. Intuition and autism: a possible role for Von Economo neurons. *Trends Cogn Sci*. 2005; 9:367–373. [PubMed: 16002323]

Highlights

- Animals and infants appear to be ‘bound’ by stimuli/events in the *present*.
- Children and adults can make adaptive use of *past* and *future* episodic memory.
- Likely related to the expansion of working memory, and social-cognitive abilities.
- Embodied sense of time may be a factor necessary for mental time travel.

Figure 1.

A summary of the notion that behavior and cognition is primitively (phylogenically and ontogenically-speaking) controlled by events in the immediate 'here and now', and this likely serves as a necessary building block for uniquely human pervasive mental time travel abilities to think about hypothetical events (outside the 'here and now')—those previously experienced (past) and imagined (future).