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Box 1. Synchrony and 'Criticality' in Animal Groups

The extremely high speed at which behavioral change (e.g., turning) or density propagates across flocks of birds (Figure 1B and Figure I) or schools of fish (Figure 1C), along with certain statistical properties observed in such groups (e.g., the presence of long-range correlations in individuals' velocity despite the presence of highly local interactions), has caused some researchers to speculate that such animal groups, as has previously been suggested for the brain, are 'poised near criticality' [6]. Taken from statistical mechanics, the theory of critical phenomena demonstrates that certain generic properties appear in a collective system, be it of physical particles, neurons, or birds, when local interactions are tuned in a certain way. Near the critical point, remarkable properties emerge spontaneously, such as individuals' behavior becoming correlated irrespective of the distance between them (which is mathematically equivalent to information being able to propagate almost without loss over the entire structure). Biological systems may benefit from being close to a critical state in a variety of contexts since they must often satisfy two, seemingly opposing survival conditions: to respond quickly to changing environmental conditions, such as the appearance of a predator, and to remain robust and organized in the face of noise (e.g., in the case of fish or birds, eddies or gusts of wind, respectively). While still controversial, criticality provides a fascinating, plausible, and increasingly testable hypothesis for effective information processing in large collectives.

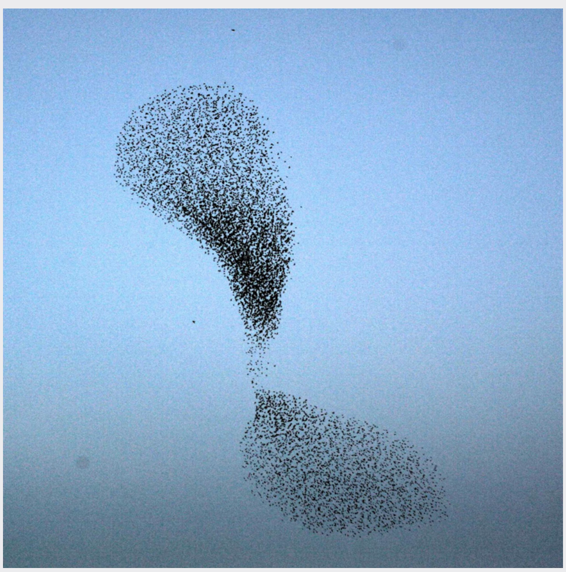

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Figure I. A 'Murmuration' of Starlings (*Sternus vulgaris*). Here the flock is being attacked by a peregrine falcon (*Falco peregrinus*) just to the left of the center of the flock. Photograph courtesy of the COBBS Laboratory, Institute for Complex Systems, National Research Council, Rome, Italy.

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Special Issue: Time in the Brain

Forum

Stuck in the Present? Constraints on Children's Episodic Prospection

Simona Ghetti[1,2,*] and Christine Coughlin[3]

The examination of children's ability to simulate their future has gained increased attention, and recent discoveries highlight limitations in this ability that extend into adolescence. We propose an account for this protracted developmental trajectory, which encompasses consideration of retrieval flexibility across timescales and self-knowledge. We also identify avenues for future research.

We spend considerable time imagining what our future might bring, savoring a desired turn of events or dreading the opposite. The mental simulation of a future event sometimes includes so much vivid detail that it subjectively approaches the experience of an actual memory. This form of mental simulation has been referred to as episodic prospection (or episodic future thinking) and has received considerable attention for its hypothesized adaptive function: the mental pre-experience of a personal future event – as opposed to knowledge or understanding of it – may provide a stronger motivational basis for future-oriented action in the present [1]. For example, it makes intuitive sense that a student might work harder through difficult class assignments if she can visualize herself going through the process of completing them. Some research has lent support to this adaptive benefit by showing a positive effect of episodic prospection on decision-making and emotion regulation [2].

Given this adaptive function, a growing body of literature has attempted to characterize the building blocks of episodic

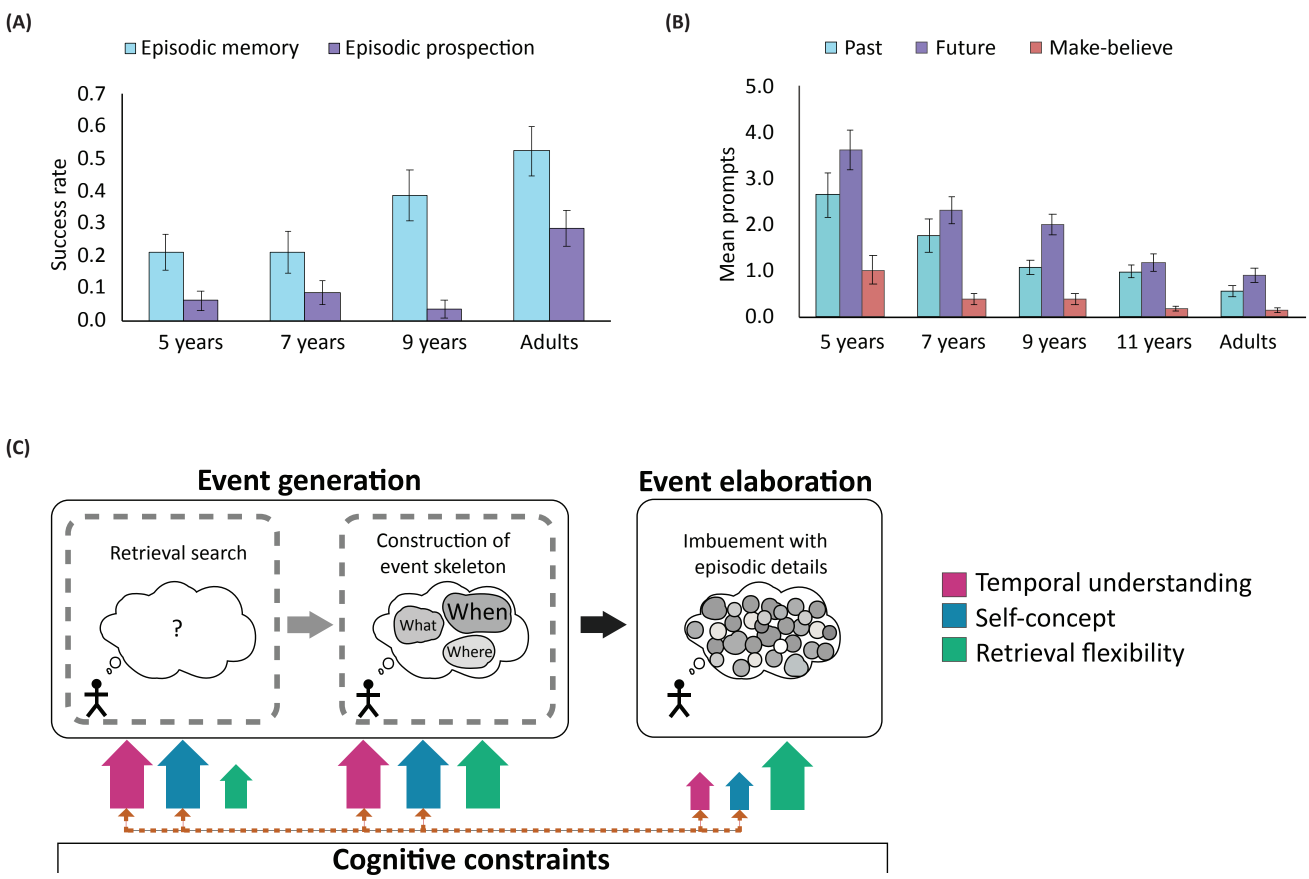

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Figure 1. Episodic Prospection Follows a Protracted Developmental Trajectory. (A) Mean success rate (±SE) of episodic prospection versus episodic memory in 5- to 9-year-old children and in adults (0 = failure, 1 = success; success indicates that children's narratives included a description of an event isolated in space and time, and with additional episodic detail). Adults were more successful at episodic prospection compared to all child age groups. Although children were able to provide narratives in all cases, they failed to include episodic detail. Reproduced and adapted, with permission, from [4]. (B) Mean numbers of prompts (±SE) required to generate personal past, future, and make-believe events for 5- to 11-year-old children and adults. Required prompts decreased with age, and 5- to 9-year-old children required more prompts to generate a personal future event than to generate either a personal past or make-believe event. Reproduced and adapted, with permission, from [5]. (C) Model of key cognitive constraints on episodic prospection ability during childhood. The event construction phase (from the dominant account developed within adult research [8,12]) is explicitly divided into two subphases – an initial retrieval search to identify a target event and construction of event skeleton – given evidence that initial event generation is particularly difficult for children [5]. Temporal understanding, self-concept, and flexible retrieval are put forth as crucial cognitive constraints, each contributing differentially to the generation and elaboration phases, and a bidirectional relation between temporal understanding and self-concept is noted. While additional cognitive processes contribute to episodic prospection (e.g., working memory and narrative ability), they are not represented within this model because they are considered to be less specifically central to difficulties with episodic prospection across childhood and early adolescence.

prospection during development. Substantial work has focused on its emergence during preschool years, examining the capacity to engage in preparatory actions for an immediate future situation based on a recent past event; this work has emphasized developmental limitations in the retention of detailed memories and conceptual understanding of mind as key factors [3]. We focus here instead on an emerging line of research that examines the development of episodic prospection beyond the preschool years, and which reveals striking developmental constraints and significant gains across childhood and into adolescence [4–6].

Why Is Episodic Prospection a Late-Developing Skill?

From an early age, children exhibit a considerable conceptual understanding of how past and future are linked, including notions about the effects of past experiences on one's future emotions and behaviors [7]. It is perhaps surprising then that even preteens continue to exhibit measurable limits in their ability to imbue their mental simulations of the future with episodic detail [4] (Figure 1A). Although adults also experience difficulties with episodic prospection [2], children's difficulties may be disproportionately stronger relative to their abilities to remember their past [4]. We are beginning to learn about the nature of these limitations.

Retrieval Flexibility across Timescales

An initial hypothesis focused on developmental changes in the capacity to engage in flexible retrieval. Episodic memory supports episodic prospection by providing the content for one's future event simulations [8]: the extent to which one can flexibly retrieve and recombine content from episodic memory may thus support the ability to simulate future events. Indeed, associations between episodic memory and prospection have been documented throughout development, and just as episodic memory continues to improve into adolescence, so too does prospection [4–6]. However, episodic prospection is more challenging across ages and appears to improve at a slower pace than episodic memory [4]. This suggests that children may suffer from the increased flexibility demands of prospection compared to episodic memory. A large body of literature has documented limits in retrieval flexibility in children [9]. Yet, when 5- to 11-year-old children are asked to provide narratives of make-believe events, which also require the flexible recombination of episodic details to generate novel events, their level of episodic detail is comparable to that included in narratives of past events [5]. This suggests that a demand for flexible recombination *per se* may not fully account for their difficulties. Producing a make-believe event is different from envisaging a future event in that the former does not require any consideration of temporal constraints. Previous research has shown that memory for temporal context reaches adult levels later than memory for other contextual features, that this deficit extends into adolescence [10], and that children's understanding of temporal information or timescales (e.g., indicated by responding correctly to questions such as 'When moving backwards from May, do you come to September or January first?') predicts temporal memory [11]. This understanding develops during childhood and likely constrains how children attend to or appreciate temporal aspects of their experiences. Episodic prospection requires consideration of temporal elements, not only to retrieve but also to construct a novel temporal context (e.g., future month, day, time of day, order of event actions). Thus, integrating episodic details across timescales may contribute to the slow trajectory of episodic prospection, a hypothesis that still awaits empirical investigation (Box 1).

Box 1. Questions for Future Investigations

How are the understanding of temporal concepts and episodic prospection related? Reports of developmental associations between memory for temporal context and an understanding of conventional timescales [11] motivate the question of how temporal knowledge influences episodic prospection in children.

How does integrating temporal information into one's self-concept affect the development of episodic prospection? Despite an observed relation between present self-concept coherence and episodic prospection [5], little is known about how a developing ability to view one's self as extended in time – from past to future – contributes to the development of episodic prospection.

What is the relation between episodic prospection and other forms of future-oriented thought (e.g., temporal discounting, planning, future orientation)? An understanding of commonalities and differences might shed new light on appropriate taxonomy [14] and developmental trajectories.

Does fostering episodic prospection in children result in adaptive benefits? Interventions targeting episodic prospection and/or other forms of future-oriented thought may help children to become 'unstuck in time' and experience benefits earlier than they would otherwise.

How does children's environment affect the adaptive value of episodic prospection? Risky or unstable environments may promote present-oriented thought to respond to immediate threats, whereas nurturing or stable environments might promote future-oriented thought or behavior.

Identification of Personally Relevant Information

An additional non-mutually exclusive hypothesis involves a difficulty with identifying which elements of the past are relevant for the future. In an initial study of episodic prospection [4], we anecdotally noted that even children as old as 9 years of age hesitated considerably when we asked them to build narratives about their future based on cue words. According to the constructive episodic simulation model, a dominant account developed within adult research, episodic prospection requires the flexible recombination of elements from one's episodic memory so as to construct the skeleton of the future event representation and to elaborate on it by enriching it with details ([8], see [12] for an update). We asked whether these construction and elaboration phases would be sufficient for a full account of the development of prospection. We proposed that, before constructing a mental simulation of a future event, one must first constrain the retrieval search to generate a suitable future event that is personally plausible. This initial step is implied but not emphasized in the constructive simulation model, likely because typical adults readily recognize plausible events. We considered that children might have a limited ability to use their self-knowledge to make predictions about their personal future and identify events that fit within these expectations. Two predictions resulted from this proposal. First, we predicted that younger children would exhibit greater difficulty in generating the initial idea of a future event in response to a cue, and would therefore need disproportionately more prompts to do so. Second, we predicted that children with a more coherent self-concept would produce richer narratives about their anticipated future, given that self-concept provides the knowledge structure necessary for constraining retrieval searches to access self-relevant information from autobiographical memory [13].

We found evidence consistent with both predictions [5]. First, 5- to 9-year-old children required a greater number of prompts for future events than did adults (Figure 1B). This developmental pattern was largely attenuated when we examined necessary prompts for past and make-believe events, bolstering the case that future event generation presents a unique challenge for children and that the demand for retrieval flexibility alone cannot account for this challenge.

Second, we found strong age-related increases in self-concept coherence, and individual differences in self-concept coherence predicted episodic prospection above and beyond other variables, including age, narrative ability, and episodic memory, which were also associated with prospection. This result underscores that the importance of self-concept extends beyond the development of autobiographical memory [13]. Although our research has indicated that having a more coherent sense of self in the present may support children's selective retrieval of personally relevant information, a later-occurring integration of temporal information into the self-concept (e.g., knowledge about the stability of self or the relation between current and future self) may additionally contribute to the behavioral improvements in prospection observed into adolescence. Research should also compare the influence of general semantic knowledge versus self-knowledge on the ability to generate a personal and plausible event because this could help to elucidate the specificity of the observed relation.

Concluding Remarks

The examination of the development of episodic prospection beyond early childhood has only recently begun to attract researchers' attention. The limits discussed here (Figure 1C) may be consequential for the ability of children to profit from the adaptive benefits of prospection at a time when they may otherwise have the capacity to enjoy increased independence and exert some control over their decisions. Future investigations (Box 1) examining the limits we have identified as well as potential sources of environmental influence may provide opportunities to better understand why children are sometimes stuck in time, as well as their developing ability to overcome this state so as to benefit from prospection.

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Special Issue: Time in the Brain

Forum

Towards Ecologically Valid Interval Timing

Hedderik van Rijn [1,*]

Research on interval timing has provided significant insight into how intervals are perceived and produced in well-controlled laboratory settings. However, for timing theories to explain real-world performance, it is imperative that they provide better quantitative predictions and be applicable to timing tasks that are relevant in ecologically valid settings.

Introduction

Whether it is using a well-timed silence during a speech to increase rhetorical effectiveness, determining whether one can finish reading a paragraph in the newspaper while keeping an eye on the children, or deciding when to initiate the final, irreversible stage of a landing procedure of a large commercial airplane, timing is an essential feature of almost all complex, ecologically valid behavior. Consequences of inaccurate timing range from less-effective communication and unintended but innocuous artwork on the walls, to lethal accidents. Thus, being able to predict how and when humans accurately estimate the duration of relative intervals from hundreds of milliseconds to a few minutes is crucial to explain how optimal behavior in complex tasks can be achieved.

Regrettably, although decades of research on interval timing have provided significant insight into how intervals are perceived and produced in well-controlled laboratory settings (e.g., [1]), the fact that these settings bear little relation to 'real life' makes it difficult to generalize the obtained knowledge to realistic task settings [2]. For example, although laboratory studies have demonstrated that timing is influenced by a wide spectrum of external factors, it is unclear to what extent these effects generalize to temporal aspects during decision making (e.g., [3]) or, more specifically, to a pilot's time-based decision about initiating the final stage of a flight. For the timing field to have an impact in the real world, it is imperative that timing theories should: (i) provide quantitative predictions; and (ii) be applicable to the type of timing tasks relevant in ecologically valid settings. Below I argue why current theories fail on either or both accounts, and what aspects need to be taken into account in future theorizing.

Characteristics of Ecologically Valid Timing

A critical challenge for models based on laboratory-based timing tasks is that these types of models all describe the timing of an interval that is purposively started in the present and will have a well-defined end sometime in the near future, allowing participants to actively attend to the passage of time (Box 1). This type of prospective timing is typically explained by assuming that there is a well-defined 'start signal' indicating the onset of the interval, after which the accrual of neural information or changes in the state of a network tracks the passing of time. However, when a salient event is observed in the real world, it is possible that at a later point in time one will need to assess how long ago that event happened. As events are encountered frequently, theories should be able to explain how we can keep track of time for a number of these events without requiring a single clock to be explicitly reset at the start of each interval.

Although some models explicitly account for this possibility (for a review see [4]), this is difficult to achieve for the majority of timing models given their intrinsic properties. That is, prospective timing theories typically assume that time is estimated in one continuous take during which attention is focused on the passing of time. These models either (often implicitly) predict that estimation of multiple concurrent intervals is impossible or hinge on complex cognitive strategies using 'temporal arithmetic' [5,6]. The emphasis on the estimation of singular intervals is unsurprising, as there seems to be a clear dissociation between the difficulty people have with estimating multiple intervals in explicit timing tasks in laboratory settings and the ease with which humans seem to estimate the temporal characteristics of concurrent intervals in real life. However, a recent animal study [7] supports the view that concurrent timing is feasible, as rhesus monkeys can simultaneously monitor and respond to multiple temporal intervals without revealing signatures of temporal arithmetic. Thus, future models of interval timing should be able to explain how we, during a conversation with a passenger while driving, can keep track of the durations of the passenger's speech pauses, of how long ago the overtaking car disappeared in the mirror's blind spot, and whether to again check the navigational device for the next instruction.