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Towards an ecologically valid naturalistic cognitive neuroscience of memory and event cognition

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ABSTRACT

The landscape of human memory and event cognition research has witnessed a transformative journey toward the use of naturalistic contexts and tasks. In this review, we track this progression from abrupt, artificial stimuli used in extensively controlled laboratory experiments to more naturalistic tasks and stimuli that present a more faithful representation of the real world. We argue that in order to improve ecological validity, naturalistic study designs must consider the complexity of the cognitive phenomenon being studied. Then, we review the current state of "naturalistic" event segmentation studies and critically assess frequently employed movie stimuli. We evaluate recently developed tools like lifelogging and other extended reality technologies to help address the challenges we identified with existing naturalistic approaches. We conclude by offering some guidelines that can be used to design ecologically valid cognitive neuroscience studies of memory and event cognition.

1. Introduction

Highly precise recording techniques to study the brain have been developed over the last 50 years. Over a long history of more than a century, we have also developed highly controlled laboratory behavioral experiments. For instance, recognition memory tests have been widely used in the study of human memory for a number of reasons, including the relative simplicity of the testing format (yes or no responses) and the capability to use words, pictures, and other stimuli with careful control over the different features of the stimuli. Combining carefully designed experiments with highly controllable stimuli and spatiotemporally resolved neural recording techniques, researchers have identified several important neurocognitive mechanisms underlying sensation, perception, memory, and other aspects of cognition. Insights into higher-order cognition from highly contrived experimental conditions, however, may not generalize very well to more naturalistic settings. In other words, these studies may not be "ecologically valid". This concern about ecological validity (Schmuckler, 2001; Lewkowicz, 2001; Andrade, 2018) sparked a revolution in cognitive neuroscience that led to the inclusion of more "naturalistic" stimuli like TV shows, movies, radio shows, and other media. In this article, we will review this recent shift towards naturalistic cognitive neuroscience and propose a framework that can be used to evaluate the ecological validity of human memory and event cognition studies.

We begin this review with a concise historical overview of memory studies spanning from Ebbinghaus' pioneering work using nonsense syllables to more recent studies using modern-day methodologies, focusing on the evolution of ecological approaches in the study of memory. We propose that a necessary condition for ecological validity is that the stimuli be *relevant* such that they engage the target cognitive processes. Therefore, we briefly review the wide range of materials used in memory research to engage various memory processes but conclude that the relevance of materials is not a sufficient condition for ecological validity. We then define ecological validity in greater detail and develop a framework for evaluating ecological validity by considering the interplay between the naturalism of the task settings and the complexity of the target cognitive phenomena. Following this, we discuss a few neurocognitive studies of human memory that illustrate the conditions we identify as critical for enabling ecological validity. Furthermore, we use this framework of the alignment between task settings and the target cognitive phenomena to critically examine "naturalistic" studies of event cognition. Finally, we discuss how modern technologies such as lifelogging, Virtual Reality (VR), and Augmented Reality (AR) combined with mobile brain recording techniques can enhance experimental control without sacrificing naturalism. See Fig. 1 for a graphical overview of this review.

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2. History of ecological validity in memory studies

The importance of ecological validity in cognitive science research has long been recognized (Neisser, 1982; Gibson, 2014; Neisser and Winograd, 1988; Kvavilashvili and Ellis, 2004). However, achieving a balance between experimental control and naturalism can be a challenging task. Naturalism is generally given up in laboratory experiments in favor of precise control of variables. While this allows for rigorous manipulation of critical variables and the accuracy of measurements, it may limit the generalizability of the findings to real-world settings. Conversely, naturalistic studies strike a different trade-off by prioritizing mimicry or simulations of real-world conditions over experimental control. While they capture behavior in real-life settings, the lack of control over variables can make it challenging to establish causal relationships and draw definitive mechanistic conclusions. Achieving an optimal balance between experimental control and naturalism is crucial for producing robust and generalizable research findings. We will examine the notion of ecological validity in detail in a later section. Here, we start by briefly highlighting some seminal contributions over the last century or so that will help us discuss this trade-off between experimental control and naturalism in memory research, before discussing modern technology-based approaches to ecologically valid neurocognitive studies.

Towards the end of the 19th century, at a time when higher-order mental processes were reasoned about primarily using introspective methods, Hermann Ebbinghaus, a German psychologist, inspired by Fechner's work in physiology, suggested that psychology was no different from the natural sciences in its affinity to philosophy (Ebbinghaus, 1873). Ebbinghaus set out to demonstrate that psychological phenomena could be studied by applying the scientific method and mathematical analyses. To minimize the effects of prior knowledge on his memory experiments, Ebbinghaus created three-letter "nonsense syllables" to perform rigorous experiments on himself (Ebbinghaus, 1885). Nonetheless, it was not long before people came to the realization that participants try to process information in meaningful ways and that even nonsense syllables are processed in this manner. For instance, the nonsense syllable 'PED' may be connected with the word "pedal", making it easier to recall, whereas other syllables, like "KOJ", may not be as easily associated with a well-known term, making them less memorable (Glaze, 1928; F. C. Bartlett, 1932). This realization, in part,

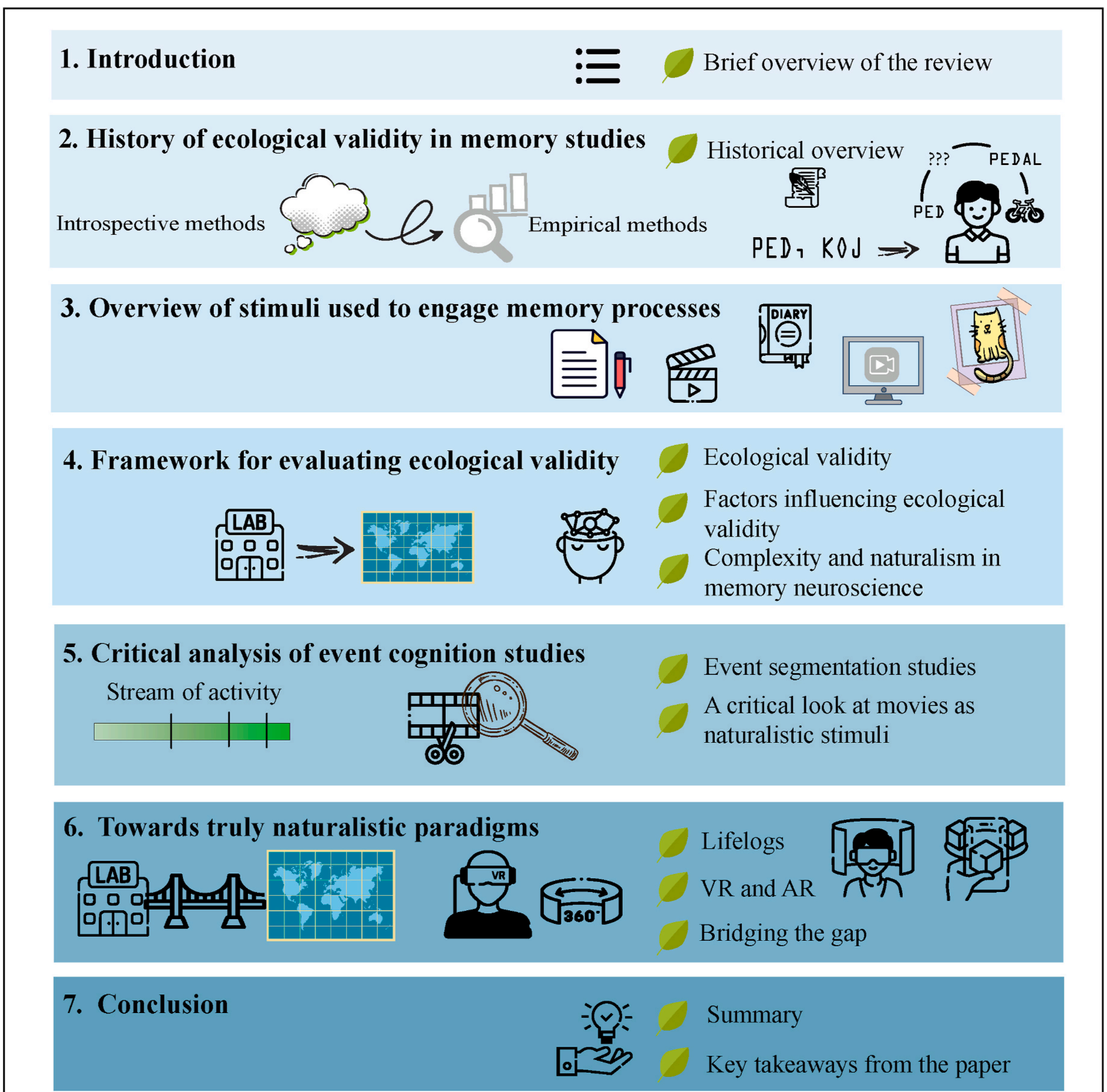

Fig. 1. A graphical overview of the topics discussed in the current review.

paved the way for a new perspective, where meaningfulness was embraced and acknowledged as an indispensable part of studying human memory (Calkins, 1896; F. C. Bartlett, 1932; Craik and Lockhart, 1972; Gordon and Clark, 1974; Craik and Tulving, 1975).

In his book, *"Memory Observed: Remembering in Natural Contexts"*, Neisser (1982) argued that in general, cognitive science research lacked ecological validity, that is, research failed to connect with the features of everyday life. While laboratory experiments were more advanced than they had ever been, scientists used temporally abrupt, random, and isolated stimuli as opposed to dynamic naturalistic stimuli that are temporally and spatially situated within richer, more meaningful contexts. Neisser urged scientists to concentrate on the nuances of the real world in which the participants actually lived, thought, and experienced things (Neisser, 1982; Braddon, 1985). Neisser argued that taking into account the variety of situations that people encounter on a daily basis can help make lab-to-land inferences about memory processes. In contrast to studies that used nonsense syllables or even meaningful words, naturalistic paradigms employ a wide range of multimodal and dynamic stimuli that mirror daily life experiences and, therefore, are better suited to investigate experience-driven reconstructive processes in memory. These naturalistic stimuli include verbal narratives, news articles, TV commercials, video clips, and simulations of real-world interactions (Sonkusare et al., 2019; Grall and Finn, 2022). It should be noted that attempts to use naturalistic paradigms in neurocognitive studies date back much further, long before Neisser emphasized the importance of *ecological validity*, a term coined by Brunswik (1947). For instance, various meaningful stimuli, such as narratives, images, and patterns varying from simple line figures to more complex squiggles to hand-drawn figures, were used fairly early on to study human memory (F. C. Bartlett, 1932). The value of using naturalistic stimuli such as movies was also demonstrated in an older EEG study that observed functionally relevant occipital sharp waves when participants watched films, referred to then as 'moving pictures' (Gastaut and Bert, 1954).

Other naturalistic methods of data collection in memory experiments such as diary studies slowly gained popularity over time (Cohen and MacNeilage, 1974; Schumann and Schumann, 1977; Csikszentmihalyi et al., 1977; Bower, 1981; Rubin, 1982; Thomson, 1930; Anastasi et al., 1948). In a different but related method, Larson and Csikszentmihalyi (1983) used structured response forms and collected data at predetermined intervals, and this methodology came to be known as the "experience sampling method" (Reis and Gable, 2000). Diary studies and experience sampling gained popularity as they allowed researchers to record participants' experiences over time "as and when they occurred" (Iida et al., 2012; Bolger et al., 2003; Almeida, 2005; Reis and Gable, 2000). However, because maintaining regular diary entries requires training and significant effort from the participants, researchers need to be careful when choosing participants for diary studies (R. Bartlett and Milligan, 2015). The participants' control over the events they choose to record also introduces a potential selection bias, which poses a significant challenge (Thompson, 1982; Iida et al., 2012). Another difficulty is the requirement that participants retain a sense of commitment and compliance in keeping their diary entries in order for the information to be reliable enough. Thus, higher attrition rates are common in diary studies due to the extensive demands placed on participants and the longer duration of studies compared to laboratory studies (Broderick et al., 2003; Ohly et al., 2010; Iida et al., 2012).

Technology has reshaped the world in various aspects and has become an inextricable part of our lives. In the realm of research on human cognition, technology offers us powerful tools to gather data that address some of the shortcomings of previous methods, such as diary-keeping. Modern experience sampling technologies have enabled the transmission of questions about behavior and cognition to participants at intervals chosen by the experimenters, facilitating the monitoring of their experiences in a more rigorous and unbiased manner (Kane et al., 2007; Smallwood et al., 2009; Yim et al., 2019; F. T. Anderson and McDaniel, 2019). Lifelogging, another direct example of this amalgamation of technology and our lives, refers to the digital logging of daily life. Lifelogging has been increasingly used to study behavior and cognition, especially memory (Bainbridge and Baker, 2022; Fu et al., 2020; Chow and Rissman, 2017; Sreekumar et al., 2014, 2018; Nielson et al., 2015; Kubota et al., 2016; Rissman et al., 2016). However, there are limitations to lifelogging methods. These include battery life issues, privacy concerns, and other factors that can lead to the unintentional or intentional omission of events, resulting in restricted access to data (Bruun and Stentoft, 2019) ultimately resulting in selection bias. Furthermore, in neuroscience studies using lifelogging, neural activity during encoding is typically unavailable. Currently, most studies bring participants back into the laboratory for a memory test, which is when neural activity is recorded (Sreekumar et al., 2018; Nielson et al., 2015). Thus, lifelogging approaches allow for highly naturalistic cognitive neuroscience studies but lack experimental control and typically do not allow for neural measures during the initial naturalistic experiences. However, the recent development of mobile neural recording devices offers a viable solution by allowing neural activity to be recorded outside the lab (Griffiths et al., 2016; Topalovic et al., 2020; Stangl et al., 2021, 2023).

While an extended discussion is beyond the scope of this review, we also acknowledge the contributions made by ecological approaches to memory studies in non-human animals. One of the best illustrations of such an approach is Clayton and Dickinson (1998)'s demonstration of episodic-like memory in scrub jays. To demonstrate episodic memory in other animals, one needs to establish that non-human animals are able to remember not only *what* event occurred *where* but also *when* they occurred. A defining feature of episodic memory is the ability to re-experience an event by mentally traveling back in time (Tulving et al., 1972). Given that animals, unlike humans, cannot provide verbal reports, it was particularly difficult for experimenters to address the *when* question. Clayton and Dickinson (1998) found a way to answer this *when* question by leveraging scrub jays' natural behavior of caching worms and retrieving them later using memory. Scrub jays and other food-storing animals learn to adapt their food recovery strategies based on the perishability of food items. In Clayton and Dickinson (1998)'s study, scrub jays avoided searching for perishable worms when they were constrained to recover the cached food only after a long delay, preferring to search for non-perishable peanuts instead. In contrast, when they were allowed to search after a short delay, the scrub jays preferred to recover the delicious but perishable worms. These results indicated that the scrub jays remembered not only what they had stored and where, but also *when* they had cached these food items, suggesting an "episodic-like" memory. Such examples from studies with non-human animals clearly illustrate the value of ecological approaches in the study of memory. However, we will not further elaborate on findings from studies on non-human animals and limit the scope of our review to human studies of memory and event cognition.

Having set a historical context for ecological approaches to the study of memory, we will next describe the wide range of stimuli that have been used to engage various memory processes in experiments.

3. Overview of stimuli used to engage memory processes

The stimuli in an experiment need to engage the target cognitive process for findings to be valid and generalizable (Brunswik, 1956). Here, we examine the wide range of materials that have been used to study memory processes.

The use of words as stimuli dates back to the nineteenth century, where, in one experiment (Kirkpatrick, 1894), lists of items were presented to school students in varied formats (spoken words, words written on a blackboard, and actual objects denoted by the words) in order to determine the most efficient presentation mode for retention. Free recall tests after brief and longer delays revealed that students remembered the visual presentation of objects more vividly than the other forms of presentation. Furthermore, words written on the blackboard were retained better than words that were spoken, indicating that visual presentation offers visual imagery-based encoding advantages. Early free recall studies revealed that when words were presented to participants in no particular order, individuals tended to recall words that belonged to the same category together; that is, they appeared to organize words into semantic clusters even though they were not initially presented that way (Bousfield, 1953; Tulving, 1962). Thus, word stimuli engage memory processes that interact with prior knowledge about how words relate to each other. Given the pervasive role of language in human experiences, it is not surprising that words are widely used even today in various memory test formats such as recognition (J. R. Anderson and Bower, 1974, Murdock et al., 1976, Yonelinas, 1994; Popov and Reder, 2020), cued-recall (Kahana, 1996; Fisher and Craik, 1977; Nobel and Shiffrin, 2001), list-discrimination (Jacoby et al., 2013; Hintzman and Waters, 1970; Hintzman et al., 1998), etc.

While words have been the bedrock of many memory studies, experiments using images have provided further insight into how we remember information. Images capture color, form, lines, and edges typically encountered in the real world and are more vividly remembered than words (Shepard, 1967; Jenkins et al., 1967; Paivio and Csapo, 1973; Hockley, 2008; Defeyter et al., 2009). Images also allow fine-grained experimental manipulation and enable experiments such as the mnemonic similarity task (MST), which can be used to assess hippocampal function, specifically related to pattern discrimination (Stark et al., 2019). The MST is a modified object recognition task that, during the test phase, employs repeated items (images that were presented previously during the study phase), foils (new images that were not presented during the study phase), and lures that have varying degrees of similarity to the studied items. The richness offered by images helps experimenters manipulate similarity along multiple dimensions such as orientation, color, shape, size, etc., leading to different levels of similarity, which is critical for engaging the pattern discrimination abilities of the hippocampus.

While words and images have been successfully used to investigate memory, the contextually rich and multimodal scenes that we encounter in the real world are fundamentally different in their dynamics and complexity (Sreekumar et al., 2014; Sonkusare et al., 2019). Audiovisual stimuli such as movies, therefore, are perceived to be highly naturalistic (Sonkusare et al., 2019; Hasson et al., 2004; but see Grall and Finn, 2022). One of the earliest uses of movies in memory research is a study that used motion pictures to determine the reliability of children as eyewitnesses (Boring, 1916). A more recent study used a narrative film to examine the long-term memory of participants and found that events were recalled even months after viewing the films (Furman et al., 2007), suggesting that the dynamics and contextual richness of movie stimuli confer memory advantages. Another advantage of movies is demonstrated by Bartels and Zeki (2004), where the engagement of multiple parallel cognitive systems enabled the researchers to functionally map the simultaneous processing of features such as faces, language, color, and activities. The results were comparable to earlier seminal findings that focused on individual features, suggesting that precise multimodal functional mapping is possible with naturalistic stimuli. In summary, movies have helped broaden our understanding of the neurocognitive mechanisms underlying autobiographical memory (Milivojevic et al., 2015; Loughead et al., 2010) and episodic memory (Hasson et al., 2008; Ben-Yakov and Dudai, 2011).

Visuals, speech, or even words tied together, conveying information about the sequence of connected events, form a narrative (Lee et al., 2020). As individuals engage with narratives, they create mental representations of the scenes and circumstances being described within them. These representations are called *situation models* (Zwaan and Radvansky, 1998; Johnson-Laird, 1983; Zacks and Ferstl, 2016). Situation models not only help people process the current material but also enable the integration of information across similar narratives (O'Brien et al., 1998) and help predict future events when sufficient information is provided (Keefe and McDaniel, 1993; Murray et al., 1993). Critically, when there is an event break, such as shifts in spatial location or the introduction of new characters, the situation model needs to be updated so that the reader can process the new context efficiently. This update is thought to drive the increased reading times observed in such studies when there is a narrative shift (e.g., Zwaan et al., 1995). During narrative comprehension, readers attempt to maintain a single coherent picture (situation model) of the main subject, such as a protagonist in the given narrative (Garrod and Sanford, 2012). Readers make an effort to maintain both local coherence (connections between currently processed information and the immediately preceding context) and global coherence (connections between current and much older, but relevant, information) within a narrative. Even when local coherence is maintained, inconsistencies disrupting global coherence lead to increased reading times (Albrecht and O'Brien, 1993). Furthermore, the increased reading times were associated with better memory performance for the older information, suggesting that readers reprocess older information when presented with inconsistent information (Albrecht and O'Brien, 1993). Therefore, the use of naturalistic narrative texts has allowed us to investigate how people process, segment, and integrate information during the ongoing experience.

In the next section, we argue that in addition to using appropriate stimuli, studies need to satisfy other important criteria for findings to be ecologically valid.

4. A framework for evaluating ecological validity

In this section, we first define ecological validity in greater detail and then identify features of the task settings that are important for achieving ecological validity. We conclude the section by discussing some naturalistic studies of memory to illustrate the elements of our proposed framework for evaluating ecological validity.

4.1. Ecological validity

Ecological validity can be defined with the help of two concepts: *representativeness* and *generalizability* (Kvavilashvili and Ellis, 2004). Representativeness refers to how well a phenomenon can be studied in a manner that matches its real-world occurrence and context. Generalizability, on the other hand, relates to the extent to which the findings of the study apply to the corresponding phenomena in everyday life (Kvavilashvili and Ellis, 2004). Lewkowicz (2001, p.438) argues that "as long as we design experiments in ways that respect the mutuality of the organism-environment relation and replicate the dynamic, real-world nature of the perceptual environment, we should be able to generalize to the real world". Therefore, the most common use of the term *ecological validity* refers to the ability to generalize from the findings of a study to behavior and cognition in the real world. While we espouse this widely used definition here, we note that the original definition of *ecological validity* by Brunswik (1947) referred to the utility and validity of sensory cues for organisms in their natural habitat. Though this original conception of ecological validity was aimed at challenging the typical factorial design in perception experiments in which variables are controlled independently and orthogonally to one another, it is also closely related to the "representativeness" of the study design. Specifically, Brunswik (1956) proposed that generalizability is better served when the variables in an experiment are intercorrelated as they are in ecological settings and their range and distributions are representative of the conditions to which we seek to generalize the results.

To achieve representativeness and generalizability, we propose that the stimuli be *relevant* such that they appropriately engage the target cognitive phenomena in similar ways to how they are engaged in the real world. We further propose that the more complex the cognitive phenomenon is, the greater the demand it places on the naturalism of the relevant stimuli and tasks. Striking a balance between engagement of the target cognitive processes and naturalism of the relevant task settings is important for the conclusions to be ecologically valid and such a balance can be analyzed using the concepts of *experimental realism* and *mundane realism*. In the next subsection, we use these concepts to identify some key factors that enable ecological validity.

4.2. Factors influencing ecological validity

4.2.1. Complexity of the target cognitive phenomenon and the demand for naturalism

Controlled laboratory experiments typically adopt a reductionist approach by isolating specific components of interest by using well-controlled stimuli, whereas naturalistic stimuli and task settings provide a more faithful representation of the richness of everyday experience (Haxby et al., 2020), which could potentially lead to insights that have wider generalizability to real-world situations. However, this claim may not apply generally, and therefore, we will motivate the conditions that necessitate naturalistic stimuli and task settings. In particular, we argue that 1) the effort to isolate independent components underlying the target behavior becomes more futile as the complexity of the relevant cognitive processes increases, and 2) a study that has some naturalistic elements is insufficient; it is critical for the specific aspects of the stimuli and task settings that are directly relevant to the cognitive phenomenon under investigation to be naturalistic. In order to develop the first argument, we must first consider the debate about componentiality versus interactiveness in cognitive science. While the term “componentiality” refers to the idea that cognitive processes can be viewed as operations on component symbol-like mental parts, the interactiveness view embraces complexity and contends that cognition is dominated by many processes that interact at various temporal scales (Ihlen and Vereijken, 2010). We will then support the second argument by reviewing findings from highly controlled lab settings that generalize well to the real world and by contrasting that with “naturalistic” studies that differ from the real world in key ways that affect the phenomenon under study.

The “Language of Thought Hypothesis” (LOTH) (Fodor, 1975) made a strong case for a componential view of cognition and greatly impacted the way in which cognitive scientists conceptualized and investigated mental processes and representations (Fodor and Pylyshyn, 1988). According to LOTH, cognition and thinking resemble language. Language involves symbols (e.g., words) that can be combined to form meaningful sentences. Similarly, LOTH proposes that higher-order thought results from a combination of simpler constituent mental elements. The traditional view, therefore, is that certain component processes can be combined linearly and causally to produce cognition. However, such a component-heavy framework might have difficulties addressing the context sensitivity of many “effects” in cognitive science. Subtle differences in experimental setup and instructions can have large influences on the behavioral patterns observed in these experiments (Stephen and Van Orden, 2012). Context sensitivity, however, is a well-known property of complex systems. In such systems, interacting parts lead to emergent higher-level phenomena, which in turn also influence how the parts interact. There is no single linear chain of causation but rather mutual dependence across levels and timescales (Turvey and Moreno, 2006). Therefore, when the cognitive phenomenon being studied is complex, involving several other interacting perceptual and cognitive processes, we must expect a high degree of context sensitivity. In such a scenario, trying to isolate components under contrived laboratory conditions may only offer insights that are extremely specific to the conditions under which one studies the said phenomenon and, therefore, are less likely to generalize and result in low ecological validity. On the other hand, when studying phenomena involving *relatively* fewer interacting elements (e.g., basic sensation, some fundamental aspects of perception, and some higher-order cognition, as we will discuss in the following paragraphs), effects may be less sensitive to minor changes in the experimental setup. Fig. 2A depicts this proposed relationship between the complexity of the target cognitive phenomenon and the demand it places on naturalism for an ecologically valid investigation.

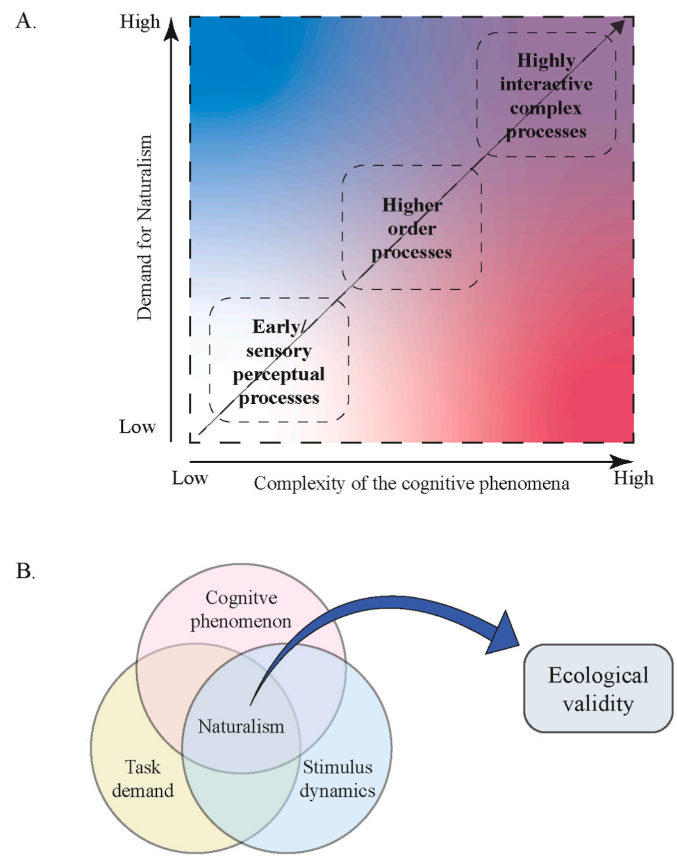

Fig. 2. Features of the cognitive phenomena, tasks, and stimulus settings that contribute to ecological validity. (*A*) A graphical depiction (inspired by Fig. 4 in Kay et al. (2023)) of the relationship between the complexity of the cognitive phenomena on the X-axis and the demand for naturalism in the experimental design on the Y-axis. We propose that the higher the complexity of the phenomena, the greater the demand for naturalism. Note that the color purple indicates the intersection of high complexity and higher demand for naturalism; conversely, white indicates the space that includes phenomena of lower complexity and the corresponding low demand for naturalism in the experimental paradigm. The simpler phenomena include the early sensory and perceptual processes; the higher-order phenomena involve the ones that have few interacting processes, such as the global similarity computation underlying recognition memory; and finally, the highly interactive complex phenomena, such as event segmentation, involve multiple interacting processes. (*B*) Naturalism achieved in the study design at the intersection of cognitive phenomena, stimulus dynamics, and task demand enhances the ecological validity of the investigation.

While the complexity of a phenomenon dictates the overall demand for naturalism in the experimental setup, certain components of a task and/or stimuli may be most relevant to the cognitive process under investigation. Consequently, it is crucial for those specific components to be naturalistic, even if naturalism is sacrificed in other aspects for practical reasons. To make this argument, we will review some traditional laboratory tasks that have led to widely generalizable findings and identify the features that enabled such generalizability. In contrast, we will pick a more complex cognitive phenomenon typically studied in “naturalistic” settings, but we will argue that the key components of these settings that are most relevant to the target cognitive phenomenon are not naturalistic enough, making findings less likely to generalize, especially to real-world settings.

In laboratory recognition memory studies, participants are presented with a sequence of stimuli and are subsequently required to recognize whether each stimulus is new or has been previously encountered. Through the manipulation of various factors, such as the strength of the association between stimuli or the length of the stimulus list, researchers can empirically test the predictions made by mathematical models devised specifically to explain memory encoding and retrieval in such tasks. In a major class of such models, retrieval occurs through a global matching mechanism where the similarity between the probe item and items studied previously is computed. Similarity values are aggregated to produce an index of global similarity, which forms the basis of the recognition decision. Such models of human memory are an impressive success, as the storage and retrieval mechanisms present in global matching models generalize well to natural language processing applications (Kwantes, 2005) as well as to other domains such as spoken word recognition (Goldinger, 1998). The universality of these models' global matching mechanisms can be attributed to the possibility that memory retrieval in many different task conditions relies on a fundamental computation of similarity between the probe and stored memories (Osth and Dennis, 2020). However, Hintzman (2011) argued that the theories developed to parsimoniously explain behavioral patterns from isolated episodic memory experimental paradigms such as recognition memory will never generalize to memory as a whole. While this argument should be considered seriously when developing general theories of memory, we claim that there are real-world situations where global-matching-like computations are likely, given that these mechanisms have been demonstrated to generalize well across tasks and stimuli. For example, recognition memory and signal detection theories have played an important role in updating our understanding of the reliability of eyewitness identifications (Gronlund and Benjamin, 2018; Meissner et al., 2005; Loftus, 1996; Loftus and Zanni, 1975; Wells and Loftus, 2003; Wells et al., 2006; Mickes and Wixted, 2020; Clark, 2003), with important real-world relevance. In other words, the fundamental mechanisms underlying less complex cognitive phenomena identified through laboratory experiments are likely to generalize well to the real world.

Having discussed how some insights from artificial laboratory settings can generalize well to other situations when the relevant cognitive phenomenon is relatively less complex, let us examine a contrasting example of "naturalistic" paradigms that are typically used to investigate a more complex cognitive phenomenon but do not guarantee the ecological validity of findings. Event segmentation, our ability to automatically parse continuous streams of experience into meaningful events (Zacks and Swallow, 2007), is thought to involve several interacting processes. Event Segmentation Theory (EST) postulates that event boundaries are generated through the interaction between existing knowledge structures, working memory, and prediction errors (Zacks et al., 2007). Other theories propose that event boundaries may also be driven by changes in latent causes (Gershman et al., 2017), contextual shifts (Clewett et al., 2019), and clustering of temporal context (Schapiro et al., 2013). Thus, bottom-up and top-down processes all interact in various capacities to drive event segmentation differently for different people. In conclusion, event segmentation serves as an illustration of a cognitive process that is likely quite context-sensitive.

To illustrate the context-sensitive nature of event segmentation, we now consider a canonical finding in the event segmentation literature. Memory for the temporal order of items has been widely reported to be better when the items are taken from the same events compared to when they come from different events (DuBrow and Davachi, 2014; Shin and DuBrow, 2021). This effect of event boundaries on temporal order memory was discovered using an extremely simplified but highly controlled notion of events and boundaries. For example, DuBrow and Davachi (2013) presented a stream of images consisting of objects and faces to the participants (also see DuBrow and Davachi, 2014). They instantiated event boundaries as a shift in the categories of the images presented, i.e., faces to objects or vice versa, and found that temporal order memory was well preserved for items encountered within the same events but was disrupted across event boundaries. In this case, there are reasons to suspect that the temporal order memory results may be an artifact of the artificial nature of the materials and experimental design. The abrupt and repeated switching between faces and objects is quite removed from the sorts of dynamic experiences we have in the real world. For instance, it is often quite easy to remember whether we stepped into our office first or that of a colleague on our way to work, as these are unique sequences of events, and we have additional context available to us in the form of familiarity or knowledge of typical transition patterns in our lives. However, remembering precisely whether we read our email before working on the manuscript in our office may be more difficult. Thus, temporal memory for experiences that span multiple unique events may be better than temporal memory for experiences within one event in our everyday lives. Indeed, recently, Wen and Egner (2022) modified the experimental design of DuBrow and Davachi (2013) by using unique encoding contexts to reduce memory interference. Furthermore, some aspects of the encoding contexts were directly available to participants at the time of the temporal order memory test, making it easier to retrieve the appropriate context required to answer the order memory question. This new design, prompted by intuitions about real-world experiences, demonstrated that temporal order memory was better for items taken from different events compared to those from the same events, essentially flipping the earlier canonical results. In the real world, item-context bindings are formed in familiar contexts. Furthermore, real-world contexts tend to be unique and distinguishable from each other. Retrieving these contexts later may be much easier than retrieving context in an experiment involving repeating categories, which leads to interference in memory. Therefore, the Wen and Egner (2022) study illustrates that the key components of the task and stimuli should resemble the characteristics of real-world situations to which we want to generalize our findings.

It is interesting to note that the results of DuBrow and Davachi (2013) were replicated in a more "naturalistic" study in which participants navigated in a virtual environment from one room to the next (Horner et al., 2016). Event boundaries were instantiated using spatial boundaries when participants made turns to go to a different room from the one they were in. In each room, two images of objects, randomly selected from a database of man-made and natural objects, were presented to the participants. A temporal-order memory test revealed that participants exhibited better memory for objects encountered within the same room than for objects shown in adjacent rooms. Even though the Horner et al. (2016) study was "naturalistic" on the surface, the objects were unrelated to each other and the contexts in which they were presented, and therefore offered no cues for context reconstruction at test, unlike the real-world conditions to which we aim to generalize such findings. Taken together, the results of these studies (DuBrow and Davachi, 2013; Wen and Egner, 2022; Horner et al., 2016) show that some naturalism in the study design by itself does not guarantee ecological validity. Therefore, for a naturalistic study to be ecologically valid, it matters that the stimuli and experimental contexts relate to each other as they do in the real world (e.g., systematic patterns of co-occurring stimuli in certain contexts like coffee mugs, laptops, desks, and chairs in an office context). Indeed, having experimental variables be related to each other as they are in the situations to which we seek to generalize our results is a key recommendation in the original conception of ecological validity and "representative design" by Brunswik (1956). Event segmentation is typically studied under "naturalistic" conditions involving movie watching. As we will elaborate in section 5, movie stimuli typically used in such studies are quite unnatural in the aspects that are critically relevant for event segmentation, such as the nature of events and the transitions between them, which in turn raises questions about the ecological validity of such "naturalistic" tasks. For these reasons, we suggest that to ensure ecological validity, in addition to placing a greater emphasis on naturalism in general for more complex phenomena, we must also consider whether the tasks and stimuli that are most relevant to the cognitive phenomenon under investigation accurately reflect the demands placed on the cognitive system in daily life. Thus, naturalism must be emphasized at the intersection of cognitive phenomena, task demands, and stimulus dynamics, as depicted in Fig. 2B.

4.2.2. Experimental and mundane realism

In social psychology, Aronson et al. (1998) coined the terms "experimental realism" and "mundane realism" to describe two different approaches to experimentation. Experimental realism prioritizes designing experiments in a manner that efficiently engages the participants in the experimental process and yields meaningful results pertaining to the targeted psychological processes (Wilson et al., 2010). In contrast, experiments with mundane realism focus on the extent to which an experiment can replicate the real world and the experiences we have, i.e., be as naturalistic as possible. Ultimately, even mundane realism does not guarantee the ecological validity of a study, and as we argued in the previous section, ecological validity depends on the intersection between the features of cognitive phenomena, task demands, and naturalism of the stimulus structure and dynamics.

In the case of memory studies, paradigms that use movie stimuli typically target experimental realism, whereas studies that use extended reality techniques such as lifelogging and Augmented Reality (AR) typically target mundane realism. Lifelogs are personal accounts of an individual's daily life activities from an egocentric point of view, while AR enables the delivery of novel experiences while embedded in real-life contexts (see section 6.2 for more details). When designing a study, the research question can drive the choice between mundane and experimental realism. For example, an investigation of how extreme emotion influences memory would demand a higher degree of experimental realism. For practical reasons, scientists would benefit from choosing movies that elicit strong emotions, as real-life events are generally devoid of these emotions. However, affective experiences in laboratory experiments are quite unlike real-world experiences, and therefore, the applicability of research findings to everyday settings has been questioned (Kensinger, 2009). Therefore, it is also important to validate findings from the laboratory in mundane, realistic settings, as MacKenzie et al. (2020) did using a lifelogging device and momentary ecological assessment. Negative affect during real-world experiences did not predict memory accuracy, contrary to expectations formed based on laboratory experiments, though such preliminary results need to be verified through larger studies. While we draw a distinction between experimental and mundane realism, it is possible to view these ideas of realism on a continuum, where on the one hand we have high experimental realism, which includes paradigms employing games and movies that are specifically created to engage the participants strongly. On the other end of the spectrum, lifelogs, uncut videos of first-person real-world experiences, are high on mundane realism but may not be as engaging as a commercial film. It is also possible for a study to include elements of both mundane and experimental realism, an example of which will be discussed in the next section. Therefore, the concepts of experimental realism and mundane realism, in combination with an understanding of the naturalism demanded by the complexity of the target cognitive phenomenon, can help us evaluate the features of a study that contribute to ecological validity.

In the following subsection, we will discuss some naturalistic studies of human memory to illustrate some of the factors discussed here that contribute to ecological validity.

4.3. Complexity and naturalism in memory neuroscience

Ecological variables are dimensions of the environment that are of significance to an organism's behavior; they are multidimensional, complex, and have nonlinear interactions among these dimensions (Campbell, 1975; Cronbach, 1975). Moreover, the brain continually adapts to navigate this ever-changing, multidimensional world, which means that experimental manipulations that ignore this complexity may not accurately reflect how the brain processes information in real-world situations (Nastase et al., 2020). For instance, humans can efficiently recognize the face of an acquaintance walking in a crowd or even when the acquaintance's face is occluded by objects such as other people, vehicles, and telephone poles. In this example, the visual features of the face are the relevant dimensions, while the motion and features of the occluding objects, like other people and vehicles, become the non-relevant dimensions. To effectively operate in situations such as these, the brain continuously weighs relevant and non-relevant dimensions and contexts to navigate and distinguish between signals and noise. Therefore, eliminating complex information by isolating just a few dimensions from the real world and presenting them on the screen during lab studies completely ignores the computation that the brain must put together (Nastase et al., 2020). Here, we focus on studies that provide insights into the neural mechanisms of memory by using experimental realism or mundane realism in their study design. These studies illustrate how the research questions of interest can drive the degree of naturalism needed in the stimuli and the type of realism employed in the task design.

Understanding the neural mechanisms underlying perception and memory for our experiences involves determining both idiosyncratic and common neural activations and representations. The use of movie stimuli has been critical in this endeavor by enabling experimental realism. In a pioneering study, Hasson et al. (2004) explored the synchronization of brain activities across individuals during naturalistic experiences using functional MRI while they watched a popular movie. Brain responses at different points in the movies were surprisingly similar across individuals. High intersubject correlation (ISC) in brain activity was observed not only in the primary sensory cortices but also in higher-order association areas, including the superior temporal sulcus (STS), lateral sulcus (LS), retrosplenial, and cingulate cortices. Moreover, the network of brain regions that synchronously activate may, in certain cases, exhibit variations due to individual differences in mental imagery and semantics triggered by the stimuli (Saalasti et al., 2019) or differences in perspectives (Lahnakoski et al., 2014; Yeshurun et al., 2017) in the interpretation of the movie clips. For instance, while participants watched an ambiguous film or listened to a verbal description of the same film, a similar interpretation of the film led to greater cross-subject similarity in brain activity in a subset of right-lateralized DMN regions, which included the angular gyrus, DLPFC, and PMC (Nguyen et al., 2019). However, are these findings from movie-watching studies relevant to life experiences and autobiographical memories that are inherently unique to people?

Studying autobiographical memory presents a challenge due to its highly idiosyncratic and context-dependent nature. Specifically, individual recollections of the same event may vary significantly, influenced by diverse factors such as emotional states, attentional resources, and prior experiences (Jääskeläinen et al., 2021). In the brain, the default mode network (DMN) structures and hippocampus are observed to be more significantly involved in processing tales expressing personally relevant autobiographical memories than in non-autobiographical narratives (Loughead et al., 2010). The interaction between the anterior hippocampus and precuneus is essential for the involuntary retrieval of memories formed during natural viewing (Ren et al., 2018). Therefore, autobiographical memory is a complex, higher-order cognitive phenomenon that demands a higher degree of naturalism. The collection of facts about one's own life, termed personal semantics, is another component of autobiographical memory that cannot be studied using less naturalistic and personally irrelevant stimuli in the laboratory, underscoring the demand for mundane realism in the paradigm. Therefore, Sreekumar et al. (2018) recruited participants to wear a lifelogging device that automatically captured images from their own lives. Participants also provided labels for each event, which were used to understand the brain networks that represent personal semantic information during autobiographical memory retrieval. This highly naturalistic approach revealed that the precuneus and the posterior cingulate cortex (PCC), a part of the posterior parietal cortex, were key areas of the personal semantics network underlying vivid reminiscence of autobiographical events (Sreekumar et al., 2018). Thus, these studies demonstrate that the DMN is crucial for the ongoing perception and memory of naturalistic events. An earlier study identified brain regions relevant to episodic memory retrieval of controlled laboratory stimuli in comparison to autobiographical stimuli (Cabeza et al., 2004). Images of campus clicked by participants served as autobiographical stimuli, whereas images clicked by others of the same locations on campus served as control stimuli. It should be noted that, even though images clicked by the participants possess personally relevant cues, the images collected by freely moving and behaving humans contain stronger personally relevant cues, which may have been critical for revealing the precuneus representations of personal semantics during vivid reminiscence (Sreekumar et al., 2018). Furthermore, the use of lifelogs enabled a critical real-world test of hippocampal space and time representations for temporal differences of up to a month and spatial distances of up to 30 km (Nielson et al., 2015), which would not have been possible with a more controlled setup as in Cabeza et al. (2004), demonstrating the value of mundane realism for answering certain questions about autobiographical memory.

Our autobiographical memories are often incorporated into personal narratives that include several events, some of which span across different temporalities and places (Milivojevic et al., 2015). In order to understand how the brain integrates information across distinct and distant events that form a coherent narrative, Milivojevic et al. (2015) used life-like animated videos involving replications of daily life activities, including interactions between agents. The videos were created such that a few of the events could be woven into a logical story, while others could not. The participants were asked to determine which videos formed a narrative and which ones did not. Higher neural similarity was observed for events that could be integrated into a narrative in the mPFC, the posterior hippocampus, and other nodes of the autobiographical memory network compared to events that could not be woven into a coherent narrative. In contrast, neural patterns were dissimilar in the posterior hippocampus for events with different narratives. To answer a related question about experiences involving similar people and contexts, Reagh and Ranganath (2023) used naturalistic video clips and found that information about people and contexts was represented in different cortico-hippocampal regions. The anterior temporal (AT) network represents information about people, generalizing across contexts, while the posterior medial (PM) network represents contextual information, generalizing across people. Additionally, the hippocampus maintained event-specific representations, allowing for the separation of distinct but similar events in memory. The use of engaging movies that portray daily life activities enabled both mundane and experimental realism, allowing participants to naturally organize events as they would in their daily lives through the formation of narratives across events and generalizations across contexts and people.

While the studies reviewed so far focused on the individual nature of autobiographical memory formation and retrieval, it is well recognized that memory is a reconstructive and social process (Kolodner, 1983; Hasher and Griffin, 1978). For example, we often recall and narrate the events of our lives to others, and this very act of recalling events can alter the contents of the stored memory. To understand the shared neural substrates of such socially shared memories, Zadbood et al. (2017) compared the neural activations during firsthand experiences and secondhand accounts of the same events. To achieve this, they built upon earlier work by J. Chen et al. (2017), who recorded brain activity while participants watched a film and then recorded their verbal accounts of it. The verbal narration and fMRI data of one participant from this earlier study were selected based on above-average recall performance. Subsequently, Zadbood et al. (2017) conducted an experiment where one group of participants watched the movie while the other listened to the recorded narration. A scene-specific correlation was observed in the neural activity recorded while viewing the movie, recounting its events, and listening to its recorded narration, suggesting that reinstatement of the neural patterns during spoken recall and scene reconstruction when listening to a secondhand account involved common neural substrates. Thus, naturalistic movie-watching, recalling, and listening tasks combined with neural recordings have enabled the study of the social and reconstructive nature of memory.

Some of the more naturalistic paradigms, upon closer inspection, may not be naturalistic enough in the dimensions that matter for the target cognitive phenomenon under investigation. In the next section, we will revisit event segmentation in greater detail and also challenge the assumption that movie stimuli provide truly naturalistic settings for studying this complex cognitive phenomenon.

5. Critical analysis of event cognition studies

5.1. Event segmentation

Analogous to how segmentation of visual scenes into their spatial elements helps us perceive objects and the relationship between the different spatial elements (Biederman, 1987), segmenting events in time as they unfold is crucial for event comprehension. Event segmentation is the process of parsing a continuous stream of information into meaningful units called events (Zacks and Swallow, 2007). Event segmentation unfolds automatically and results in a hierarchical organization of events (Zacks and Swallow, 2007; Baldassano et al., 2017). For instance, if you are traveling from your house to the airport, hailing a cab, the ensuing cab ride, and reaching the airport could be considered coarse-grain events, whereas smaller actions like loading luggage into the cab, passing various checkpoints, and paying the fare constitute fine-grain events. Fine-grained events are nested within coarse-grained events such that coarse-grained event boundaries reflect the grouping of finer-grained events (Newtson, 1973). Top-down knowledge structures may shape coarse-grain boundaries, whereas fine-grained segmentation relies more heavily on bottom-up, stimulus-driven information (Zacks, 2004). It is with the help of these boundaries that individuals stitch together pieces of information in time to remember details about the events they encountered (Shin and DuBrow, 2021; Jeunehomme et al., 2018). Therefore, better segmenting of events leads to better event memory, indicating that event segmentation facilitates learning and memory (Zacks et al., 2006). The memory and comprehension benefits offered by event segmentation have led to a recent proliferation of studies predominantly using movies as stimuli aimed at understanding the neural and computational mechanisms underpinning event segmentation. Therefore, we will first summarize some key findings from studies that use movie stimuli.

Behaviorally, event segmentation is assessed through participants' explicit identification of event boundaries (Newtson, 1973). Interestingly, neuroimaging data from participants suggests that the brain parses videos into discrete events even when participants are not explicitly asked to, indicating segmentation processes at work even during passive encoding (Speer et al., 2003; Zacks et al., 2001b). Furthermore, participants tended to agree on the location of event boundaries (Newtson and Engquist, 1976). This segmentation agreement between participants in the behavioral data is further supported by neural evidence demonstrating the association of neural patterns to scenes of the movie and the similarity of neural patterns across participants for each encoded scene (J. Chen et al., 2017).

Brain activations at retrieval were found to be similar to the brain activations at encoding for the same movie clips, thereby implying that neural activity is reinstated when the participants recall the movie they had watched (J. Chen et al., 2017; Oedekoven et al., 2017). Furthermore, brain activity patterns are reinstated each time a video is rehearsed, with the strength of the reinstatement determining how well the participants remembered the video (Bird et al., 2015). Importantly, similar reinstatement of neural patterns of the just-experienced event is also observed at the event boundary (Sols et al., 2017; Silva et al., 2019). Memory reactivation helps in effective comprehension of the ongoing narrative in movies by integrating incoming information with reactivated past events (Hahamy et al., 2023). This integration extends even to temporally distant past events, as evidenced by activity in the hippocampus, as long as these events fit within a coherent narrative framework (Cohn-Sheehy et al., 2021).

In contrast to the encoding and retrieval-specific activity patterns described above, increased hippocampal activity was observed at event boundaries compared to non-boundary points both during the encoding and retrieval of popular movies (Ben-Yakov and Henson, 2018; Reagh et al., 2020; Magliano and Zacks, 2011) and videos of actors performing chores (Swallow et al., 2011). However, attenuation of hippocampal activity at the offset of a video was observed when it was followed by a second unrelated video in quick succession, resulting in interference in memory for the first video clip (Ben-Yakov et al., 2013), suggesting that post-event encoding processes triggered by event boundaries may be disrupted under some circumstances. Besides the hippocampus, various cortical regions are also activated at event boundaries, such as the visual cortex, the posterior parietal cortices, the VMPFC, the occipital cortex, the precuneus, the temporal cortex, the striatum, the temporoparietal junction, the angular gyrus, and the superior temporal sulcus (Zacks et al., 2001b, 2011; Ezzyat and Davachi, 2011; Betti et al., 2013). Therefore, beyond univariate hippocampal activity, successful encoding likely relies on the interactions between the hippocampus and neo-cortical areas. For example, functional connectivity activity between the hippocampus and the posterior medial subnetwork (PMN) at event boundaries during encoding was related to subsequent successful event recall (Barnett et al., 2024). Furthermore, coordinated activity in the hippocampus and PMN was also predictive of the detailedness of recall after a long delay (Barnett et al., 2024). To further understand how hippocampal activations were related to cortical signatures of event segmentation, Baldassano et al. (2017) identified neural data-driven event boundaries during continuous movie watching and found a strong relationship between hippocampal activity and neural boundaries in cortical regions such as the angular gyrus, posterior medial cortex, and parahippocampal regions. Curiously, the hippocampal response started slightly before the cortical event boundary and peaked within several time points after the boundary (Baldassano et al., 2017). In summary, the use of movie stimuli and fMRI has uncovered several coordinated cortical and subcortical neural processes underlying event segmentation. However, fMRI is not well-suited for uncovering the precise temporal relationship between neural activity in different brain regions, and future investigations will need to leverage MEG or iEEG to probe these relationships further.

Event segmentation studies frequently use commercially made movies (Zacks et al., 2010; Magliano and Zacks, 2011; Baldassano et al., 2017; Ben-Yakov and Henson, 2018), bespoke video clips (specifically created for research), where actors perform everyday activities (Zacks et al., 2001b; Swallow et al., 2011; Kurby and Zacks, 2011), and animated videos (Yates et al., 2022; Hard et al., 2006; Barnett et al., 2024). Commercial movies and TV shows, such as the ones used in much of the work summarized above, have led to an understanding of the putative neurocognitive mechanisms underlying event segmentation. Nevertheless, movies miss out on critical elements of real-world dynamics that might be essential for the cognitive processes involved in event segmentation to function and interact the way they do in our daily lives. Thus, in the next subsection, we view movies through a critical lens and weigh their standing as a truly naturalistic stimulus.

5.2. *A critical look at movies as naturalistic stimuli in event segmentation studies*

Despite bearing some semblance to real-life experiences, commercial movies are essentially crafted. Visual artists meticulously design audiovisual media to evoke desired emotions, feelings, thoughts, and ideas. Movies are directed in specific ways to express stories with the aid of extreme editorial cuts, camera angles, lights, sounds, timing, characters, heightened emotions, and other features to engage the audience. However, the very intention behind crafting movies for audiences inherently reduces their naturalistic quality, posing challenges for research. This artistic intent is best illustrated by Wes Anderson's 'The Grand Budapest Hotel', with its portrayal of whimsical characters and usage of unconventional color palettes (Vreeland, 2015). The movie's characters, while intriguing, are eccentric, and their interactions are often divergent from real-life interactions. The blend of artistic detail and cinematic richness makes the movie an example of a setting far from reality. However, 'The Grand Budapest Hotel' was still chosen in a study that aimed to observe the neural activity underlying the comprehension of social relationships, owing to its ensemble cast, "naturalism", and rich narrative (Visconti di Oleggio Castello et al., 2020).

On the one hand, commercial movies often feature fast-changing and striking context changes, driven by directors' deliberate use of strong perceptual transitions and semantic shifts to enhance cinematic value. On the other hand, the event transitions experienced in real life are smoother and more gradual. Consequently, if participants were to segment real-life events, they would escape the deliberate orchestrations of filmmakers. The high degree of agreement among participants during the segmentation of commercial movies may just be the result of boundaries being explicitly "given" to the participants by filmmakers via directorial manipulations (Mariola et al., 2022), in turn, also driving the neural effects observed during such segmentation. Therefore, the obvious and sharp boundaries in commercial movies raise the possibility that the neural synchronization patterns and other boundary-related activations observed in the fMRI scanners during movie-watching are not a faithful representation of the neural activations that occur over real-life event transitions. However, some movies like 'The Red Balloon' include a rich narrative, a limited number of dialogues, and not many abrupt cuts and have been used in event segmentation studies (Zacks et al., 2009, 2010; Magliano and Zacks, 2011). Nonetheless, 'The Red Balloon' is a masterful film, accompanied by diverse soundtracks that cater to the requirements of the scenes. Furthermore, the film evokes intense emotions for the young and innocent protagonist. Even films devoid of visible cuts, such as Alfred Hitchcock's 'Rope' or Sam Mendes' '1917', branded as one-shot films, induce strong emotions in viewers. The deliberate use of techniques such as framing, narration, editing, and the use of soundtracks by filmmakers to evoke powerful emotional reactions from viewers influences their attention and interpretation (Carroll and Seeley, 2013). Real-world events unfold without musical accompaniment, but music plays a pivotal role in movies by establishing the mood and by adding meaning to film scenes that, in turn, influence the perception and interpretation of films (Thayer and Levenson, 1983; Marshall and Cohen, 1988; Boltz, 2001; Tan, 2017; Hoeckner et al., 2011; Costabile and Terman, 2013). Furthermore, affective processes heightened by music enhance perceptual sensitivity to salient aspects of the environment. As a result, the use of such emotion-inducing cues might have significant implications for how individuals segment audiovisual stimuli (Carroll and Seeley, 2013). In addition to these intrinsic features of commercial films, participants' unique experiences can drive segmentation behavior. Given the significance of predictive processes in event segmentation, top-down influences like expectation, familiarity, and even participants' cultural backgrounds must be taken into account in experiments (Newberry et al., 2021; Massad et al., 1979; Levine et al., 2017). Neglecting these factors that are relevant for everyday life event transitions can lead to ecologically invalid conclusions.

In general, commercially made films have limitations when it comes to their usefulness in understanding how events transition in everyday life. To address this issue, a few researchers have opted for more naturalistic stimuli, such as video clips of actors performing everyday activities like setting up printers or getting coffee from a cafe (Levin and Simons, 1997; Kurby and Zacks, 2011; Zacks et al., 2001a, 2001b, 2006, 2011; Zacks, 2004; Newtson, 1973). Though these videos are still deliberately 'directed' for research purposes, they are arguably closer representations of our everyday lives than cinematic narratives. Even then, prior experience with the actions depicted may influence how one segments events. In fact, a study reported that experts segment dance videos differently than novices by identifying relatively fewer segments

(Bläsing, 2015). Given that segmenting behaviors can directly influence memory performance (DuBrow and Davachi, 2013; Wen and Egner, 2022; Zacks and Swallow, 2007; Swallow et al., 2009; Radvansky and Zacks, 2017; Flores et al., 2017), the differential grain of segmentation among experts and novices might have important implications for memory encoding and retrieval. Another critical drawback of these bespoke movies is that they typically depict single scenes from a third-person perspective. The problem with single scenes is that the transitions that one would call coarse-grained in single scenes may well be considered fine-grained when situated within a longer sequence of several scenes. There may also be meaningful differences between first-person and third-person perspectives. For example, participants identify fewer boundaries in the first-person perspective videos than in third-person perspective videos (Allé et al., 2023; but see Swallow et al., 2018). Furthermore, participants had better temporal order memory performance for the third-person perspective videos than the first-person ones, which may be attributed to the camera angles and frequent changes in focus, causing participants to lose grasp of the temporal sequence of events (Allé et al., 2023). While some recent studies have incorporated first-person perspective videos in segmentation experiments (Magliano et al., 2014; Jeunehomme and D'Argembeau, 2020), a less explored question is how people segment their own life experiences, given that they are the agents driving actions and are aware of higher-level information such as the goals underlying those actions.

Critically, a significant portion of our daily lives involves repetitive and familiar experiences (such as our daily commute to work), while some events stand out as less routine. Additionally, people frequently multitask, which may simultaneously engage different cognitive processes within the same timescales, such as talking over the phone while preparing breakfast (Sastre-Gomez et al., 2023b). Similarly, our daily life experiences are marked by discontinuities that include: 1) Interrupted events, where an ongoing event A is interrupted briefly by an event B, with event A being subsequently resumed, for example, getting interrupted by a phone call while watching a movie, which is resumed right after the phone call. 2) Interdigitated events, where people engage in two or more events concurrently by switching attention between them, for example, maintaining two different conversations with two different people on a texting application and 3) Chained events, where one grand event with a larger goal occurs in installments between other events, for example, working on a neuroscience term paper for a week adding some bits in every day (Sastre Gomez et al., 2023a). Summing up, these different types of non-contiguous events have not been used in event segmentation studies, suggesting that our current understanding of event segmentation during truly naturalistic experiences remains incomplete. Furthermore, the transitions between events in our daily lives are typically not abrupt. An example of a transition is walking from the street into a building. While this is a relatively abrupt transition, it is still far more gradual than the scene changes typical of mainstream movies. Recently, populations of neurons have been discovered that activate only for abrupt and big transitions but not for smoother transitions (Zheng et al., 2022). Based on such neural findings, it is unclear, for example, if the hippocampal engagement found at event boundaries when participants watch commercial films provides any conclusive insights about the role of the hippocampus during real-world segmentation of events with smoother transitions. Therefore, we propose that event cognition be studied using even more naturalistic paradigms using stimuli that mimic real-life familiar, repetitive, and first-person experiences with smooth transitions between events. In the next section, we review approaches based on modern extended reality technologies that can not only enable better ecological validity in memory studies but also provide ways to translate research findings to memory support and rehabilitation applications that are relevant to daily life activities.

6. Towards truly naturalistic paradigms

6.1. Leveraging egocentric videos and lifelogs

Lifelogs, as introduced earlier, offer comprehensive personal archives of people's everyday experiences. Lifelogs can include images, videos, audio, GPS, accelerometry, and even bio-signals (Dingler et al., 2021) that can later aid in reminiscence (Bruun and Stentoft, 2019). Lifelogs hold great promise as a tool for memory support for people with both retrospective and prospective memory issues (Dingler et al., 2016a; Chan et al., 2019; Y. Chen and Jones, 2010). Other applications of lifelogs include using them as a strategy for emotion regulation that goes beyond just reminiscing (Le et al., 2016) and also as a memory-based intervention tool for patients with depression (Qu and Sas, 2018).

The design and features of lifelogging devices have evolved over the last few decades. A few of the cameras, applications, and devices used so far for lifelogging purposes include the SenseCam (Hodges et al., 2006), Narrative Clip, and Google Glass. While Google Glass and other cameras are built into glass frames, SenseCam, Narrative Clip, and Autographer are chest-worn devices. The quality of the head-worn camera footage was preferred by participants over the data from the chest-worn devices with regard to perspective, camera motion blur, and situational recall value (Wolf et al., 2015). On the other hand, chest-worn devices capture stable images and videos and have advantages over head-worn cameras in recording activities and covering a wider area of the background.

Reflecting on previous experiences improves episodic memory (Li et al., 2011). Therefore, it is imperative to record relevant information that can be made available later for reflection. Lifelogs accumulate a massive amount of data, typically in the order of hundreds or thousands of images taken over a week of a participant's life. The challenge then lies in creating concise but comprehensive summaries that aid memory reconstruction. Deciding what to include in these lifelog summaries demands careful consideration and has been a subject of study in computer vision (e.g., Nagar et al., 2021). There are two approaches to designing memory augmentation solutions. The first is to create an external memory device that functions as a digital repository for lifelog data, enabling users to search and browse recorded content (Dennis et al., 2019b). For example, applications such as Google Photos and SenseCam (Hodges et al., 2006) allow users to revisit their data. The second strategy is to improve participants' memory by summarizing and processing recorded information in a way that reinforces associations between the different elements of their experiences. This can be achieved by developing algorithms to create automatic video highlights of the day that can be presented to participants at the end of each day (Dingler et al., 2021).

People, activities, and locations are crucial memory cues for recalling past events (Robinson, 1976). To effectively navigate these personal archives, metadata such as date, time stamps, and location offer systematic frameworks for organizing lifelog data, enabling users to access and explore their experiences with ease (Gurrin et al., 2014). Since we live in a technologically advanced world, our daily interactions with devices like smartphones and computers leave behind digital footprints. These traces, including browsing history, call logs, GPS data, calendar entries, text messages, etc., collectively form what is referred to as implicit captures of everyday life (Dingler et al., 2021; Rzayev et al., 2018). Smartphone applications like *ReflectiveDiary* take advantage of this passive data collection and record these digital data to reconstruct a user's daily activities (Rzayev et al., 2018). Another example of implicit data capture is the automated capture of screenshots of a user's desktop screen at regular intervals (Gemmell et al., 2002; Dingler et al., 2016b). Implicit data captures can therefore complement the visual data (footage or images) from wearable cameras, especially when they are sparsely collected, to provide much more holistic lifelogs. In particular, implicit captures are handy when recording regular, everyday life experiences that tend to be similar. For example, work on Monday may not be very different from work on Tuesday or Wednesday, which can lead to a potential blending of memories. Thus, comprehensive records of experiences can help users disambiguate between the events experienced on different days.

Integrating lifelogs into neurocognitive research has provided valuable insights into how individuals perceive, interpret, and recall events in their daily lives. Researchers have employed different protocols for lifelog studies based on their research questions. One fMRI study (Nielson et al., 2015) investigated how the hippocampus represented time and space while participants viewed and reminisced about their own life events, cued by lifelogs they collected over a month that featured activities separated by distances up to 30 km. The use of lifelogs enabled the extension of prior findings about hippocampal representations to larger real-world spatiotemporal scales. A reanalysis of the same data discovered an important role for the precuneus within the default mode network for representing personally salient semantic information, paving the way for understanding how personal semantics are represented in the brain (Sreekumar et al., 2018). Bainbridge and Baker (2022) used a social media app to capture the highlights of their users' days. Participants were asked to create 1-s videos of their day, which were then analyzed for features such as the age of memories, the strength of memories, locations, and emotional content. To counterbalance the study, participants viewed their own videos and those of another participant in an fMRI scanner. Results indicated that the medial temporal lobe contains distinguishable information about the strength of memory and emotions but not spatial locations or the age of memory, while the medial parietal cortex had distinct representations of the age of memory, memory strength, people familiarity, and place familiarity. An earlier study employed the SenseCam to capture images for two days and tested participants' recognition memory after a short and long delay of 36 h and 5 months, respectively, and found familiarity-related neural activations in the medial temporal lobe but no neural signatures of recollection after a long delay (Milton et al., 2011). These studies illustrate the value of a naturalistic approach that allows us to take memory research beyond the spatiotemporal scales possible within the laboratory environment.

While lifelogs provide a direct record of participants' lives, they are not free from issues. Since lifelogging data is quite personal to the participants and can include sensitive information, people in general may be apprehensive about sharing their data. Additionally, concerns about data leaks or personal data being sold to companies cause participants to worry enough to not consent to studies like experience sampling studies or lifelogging studies (Dennis et al., 2019a). Beyond data sensitivity, lifelogging raises privacy concerns related to the accidental capture of others and potential exposure in private settings. The constant awareness of being recorded makes participants feel like they are under observation, which can also alter their natural behaviors (Bruun and Stentoft, 2019). Additionally, if the lifelog camera requires human intervention to record events (Martin et al., 2022), it creates a different version of selection bias (which was also the problem with diary studies). Conversely, the camera may assume an almost imperceptible embodiment, subjecting individuals to the possibility of inadvertent exposure in private settings such as bedrooms or bathrooms (Clinch et al., 2016). The risk of accidental capture is often a source of infringement on privacy for both the wearer of the camera and others in the vicinity of the user. Another serious issue is the storage of such sensitive personal information about the participants' lives and how many people have access to it. To address these issues, Dennis et al. (2019a) devised solutions based on statistical approaches to privacy and handing over data ownership to the participants.

The large volume of data may sometimes make it difficult for the participant to determine the sensitivity of lifelogs they appear in. Unaware identification may allow attackers to create profiles of individuals by combining lifelog identities with other information. In a way, the participant wearing the lifelogging device also faces a lack of control over what images or data are uploaded and stored in the cloud until he has access to the files (Ferdous et al., 2017). Additionally, lifelog data are inherently variable as they capture unique life patterns across individuals. This variability does not allow the experimenter control over various confounding variables and subjective biases. One other drawback of the studies mentioned earlier is that, due to the nature of the designs, it is virtually impossible to gather brain recordings from the participants while they are out in the open collecting lifelog data. A solution is to use mobile brain recording techniques, as exemplified by some studies (Topalovic et al., 2020; Griffiths et al., 2016; Stangl et al., 2021). Alternatively, virtual reality or augmented reality setups can simulate real-world scenarios within the lab, allowing brain recordings under controlled conditions during the encoding phase of an experiment.

6.2. *Harnessing the potential of virtual reality and augmented reality*

Virtual reality (VR) has recently gained significant attention in different domains of psychological research due to its ability to create immersive and egocentric experiences, particularly in exploring emotions (Riva et al., 2007; Zlomuzica et al., 2016; Cadet et al., 2022; Pinilla et al., 2021; Martens et al., 2019; Kisker et al., 2021a), and memory (Pugnetti et al., 1998; Radvansky and Copeland, 2006; Plancher et al., 2010, 2013; Mueller et al., 2012; Yip and Man, 2013; Minderer et al., 2016; Reggente et al., 2018; Kisker et al., 2021a, 2021b; Brugada-Ramentol et al., 2022). Additionally, VR has contributed in fields such as education (Freina and Ott, 2015), social interaction studies (Collange and Guegan, 2020) and in the improvement of cognitive functions of individuals with autism spectrum disorder (ASD) (De Luca et al., 2021). VR can be described as "a medium composed of interactive computer simulations that sense the participant's position and actions and replace or augment the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation (a virtual world)" (Sherman and Craig, 2018, p. 16). Both virtual/augmented reality and movies are synthetically crafted by human beings. However, virtual reality fosters a deeper sense of engagement as participants can interact with realistic environments in real-time (Smith, 2019). Furthermore, VR gives the experimenters a significantly higher degree of control and flexibility (Bauer and Andringa, 2020), as they can simulate real-life scenarios from an egocentric viewpoint (Smith, 2019; Johnsdorf et al., 2023).

Does the immersive nature of VR drive the engagement of different cognitive and neural processes compared to 2D presentations of stimuli? Compared to traditional 2D movies, movies presented in VR not only generate higher subjective reports of immersiveness and engagement (Carpio et al., 2023), but they also evoke stronger emotion and facilitate a more vivid recollection of the narrative (Szita et al., 2018). Therefore, if event segmentation tasks are administered in VR rather than the currently dominant movie-watching paradigm, the differences in immersion and levels of engagement can potentially activate different cognitive and brain processes. Furthermore, there are many other differences between the realistic events that can be simulated in VR and the events depicted in movies (as argued extensively in section 5.2) that make it likely that different cognitive and neural mechanisms may be uncovered by using these more naturalistic paradigms in VR.

While some aspects of emotion and other cognitive processes can be different between VR and 2D presentations, others have been found to be similar. For instance, Hofmann et al. (2021) investigated emotional arousal and its corresponding neurophysiological substrates during a naturalistic virtual reality experience. Participants engaged in a realistic roller-coaster experience while their brain signals were recorded using EEG. Hofmann et al. (2021) decoded the states of higher and lower arousal levels from the EEG recordings. Their findings validated previously conducted lab-based studies on emotional arousal (Koelstra et al., 2011; Luft and Bhattacharya, 2015). Therefore, one can anticipate finding both major differences and similarities in the cognitive and neurological processes engaged by event segmentation tasks administered in 2D and VR. In future studies, direct comparisons between traditional movies and more realistic, egocentric, and immersive experiences in VR may be valuable in understanding the generality of current findings in the event segmentation literature.

In addition to the deeper immersion and engagement that it fosters, VR also provides experimenters with flexibility in creating environments and, thereby, greater experimental control over those experiences. This flexibility is exemplified in a study that contrasted incidental and intentional memory encoding in younger and older adults using both traditional verbal episodic memory tests and a task administered in a realistic virtual environment (Plancher et al., 2010). Specifically, participants drove a vehicle in a virtual environment that mimicked the urban streets of Paris with various components such as buildings, roadblocks, restaurants, etc., accompanied by sounds such as the noise of traffic. The simulated environment also included a road accident scene where two cars collided. Thus, by providing the flexibility to simulate naturalistic events in safe environments for participants, VR offers a balance between naturalism and experimental control. While other naturalistic approaches, such as lifelogging, enable mundane realism to a greater degree compared to VR, they lack experimental control over memory encoding. Although event cognition studies employing lifelogs can effectively help to study the neural underpinnings of memory retrieval, they struggle to capture neural data during the acquisition of real-world experiences. VR offers an opportunity to record neural patterns during both memory encoding and retrieval. In conclusion, VR allows for greater experimental control over the conditions in which memories are formed and retrieved (Reggente et al., 2018; Cesanek et al., 2023; Mueller et al., 2012).

Virtual reality holds potential not only for advancing memory studies but also for rehabilitation for individuals with memory deficits (Georgiev et al., 2021; but see Plechata et al., 2021 for a systematic review that found inconclusive evidence for the efficacy of VR in memory rehabilitation). For example, memory training in pathfinding using virtual environments improved memory in individuals at risk of memory degeneration (Optale et al., 2010). To further motivate the participants, the virtual environments started with places familiar to them, followed by paths (with distinct colors and markers) that led to particular destinations. Notable improvements were observed in the memory tests of the experimental group after having trained for six months. In a different experiment, stroke patients received VR training for various ordinary daily life activities (Gamito et al., 2017). The study involved activities such as grocery shopping (to train working memory), navigating a virtual market (to improve visuospatial orientation), looking for a character in yellow attire (to improve selective attention), and identifying advertisements (to improve recognition memory). After training for four to six weeks, the patients exhibited significant improvements in memory and attention, as evidenced by standard neuropsychological measures. Studies that employ virtual reality have reported general cognitive improvements in the healthy geriatric population as well (Gamito et al., 2019). Twelve sessions of memory VR training were offered to participants, who ranged in age from 65 to 85. Tasks were designed to train cognitive functions like attention, working memory, auditory memory, and executive functions with gradually increasing levels of difficulty. Subsequently, the tasks reflected frequently encountered activities, such as shopping, recalling TV news, and selecting an outfit. The VR-based cognitive training enhanced attention, visual memory, and cognitive flexibility.

Despite the advantages discussed above, VR has its limitations. In some studies employing VR, the participants lose sight of their bodies, potentially impacting their performance negatively in some cases (Pan and Hamilton, 2018). However, this issue can be addressed by providing the participants with a virtual body that accurately mirrors the position and movements of their physical bodies. Another drawback of VR is the presence of "nearly-but-not-quite human" characters in the VE, which are considered "uncanny" and might be a cause of discomfort for some participants, necessitating the use of figures with more human-like movement. Furthermore, the conflict caused by the mismatch of the input carried to the visual system and the vestibular system due to the perception of movement in the VE when there is no motion in reality results in a feeling of nausea in some participants (Pan and Hamilton, 2018). It has also been found that the interactions and experiences in a VE may still considerably differ from those in real life and are perceived as real to varying degrees by participants, which might give rise to some inconsistencies in the findings. For example, some studies have observed poorer learning outcomes due to increased cognitive load (Makransky et al., 2019; Richards and Taylor, 2015; but see Alhalabi, 2016). A few of these shortcomings of virtual reality can be overcome with the help of augmented reality.

Augmented reality (AR) allows the overlay of digital content onto the real world, creating immersive environments that are potentially even more engaging than VR (Maidenbaum et al., 2019). AR has been increasingly being used in various fields, including cognitive science (Juan et al., 2014; Tang et al., 2003; Squires, 2017; Han et al., 2021; Buchner et al., 2022). AR environments show promise as an improvement over VR in the study and rehabilitation of spatial memory (Maidenbaum et al., 2019). Hence, when coupled with mobile neuroimaging, AR can provide an even more naturalistic yet controlled environment for cognitive neuroscience studies. As in the case of VR, AR can also be used in cognitive training for elderly individuals to improve their memory (Han et al., 2021).

The use of AR offers great practical benefits in domains such as education. For instance, Carrera and Asensio (2017) mapped the 3D structures of the terrains onto the 2D landform maps to help students not only visualize terrain features and elevation but also learn to read maps and navigate in different directions. 2D maps are restrictive in terms of visualizations of the nature and elevation of the terrain; therefore, AR helped even novices read and interpret maps better. Similarly, Mendez-Lopez et al. (2022) developed an AR application that provided psychology students with detailed morphological and functional visualization of the human brain to aid learning, complementing classroom lectures and textbooks. Additionally, AR can help enhance mnemonic techniques like the Memory Palace method. This involves mentally constructing a familiar space and associating items to be remembered with specific locations within that space. However, creating and navigating these mental palaces can be challenging for novices. Rosello et al. (2016) addressed this challenge with their *NeverMind* system, which leverages AR to transform real-world environments into personalized memory palaces, for example, associating chemistry formulae with landmarks in your local park. Studies have demonstrated that content learned through NeverMind significantly improved recall rates compared to traditional memorizing methods, with the added benefits of increased enjoyment and ease of learning. Therefore, AR-based designs hold significant promise for both applied fields and basic cognitive neuroscience research.

In conclusion, both VR and AR offer multiple advantages, and in particular, such extended reality techniques could offer an ideal balance between experimental control and naturalism in cognitive neuroscience studies of memory and event cognition, as we briefly discuss in the next subsection.

6.3. Bridging the gap between naturalism and laboratory settings

A recurring theme in this review has been the tradeoff between experimental control and naturalism when targeting ecologically valid findings. In some cases, it is possible to bring laboratory-based paradigms to the real world, as in the study by Griffiths et al. (2016), where participants completed a word-based memory experiment on a tablet while their brain activities were recorded using mobile EEG equipment as they walked along spiral paths on a university campus. Conversely, some studies brought the real world into the lab, as exemplified by Nielson et al. (2015) where lifelogs were used to capture the daily life of the participant, which were then used as memory cues to determine the neural underpinnings of memory retrieval or personally relevant information spanning realistic spatiotemporal scales. The strengths of both types of studies can be combined by using extended realities and mobile brain recording techniques, facilitating neuroscientific investigations of memory in natural contexts where social interaction, agency, and embodiment all simultaneously play a role, as they do in our daily lives (Shamay-Tsoory and Mendelsohn, 2019). However, augmented reality is a relatively new technology, and the current ecosystem of both hardware and software is not mature enough for widespread adoption. However, we anticipate that rapid development over the next few years will accelerate ecologically valid AR-based cognitive science research that achieves an ideal balance between experimental control and naturalism.

7. Conclusion

The pursuit of understanding memory and cognition has evolved over time, from the use of nonsense syllables to manipulating elements of our environment using augmented reality. In this review paper, we have provided a comprehensive account of this progression. A core focus of our review paper is ecological validity. We have offered a framework for helping us evaluate whether a study is likely to be ecologically valid. This framework takes into account the complexity of the cognitive phenomena being investigated and the naturalism in stimulus dynamics and task demands that are most relevant to those cognitive processes. Next, we examined event segmentation studies through a critical lens and described some limitations of cinematic experiences in capturing the crucial aspects of naturalistic scenarios most relevant to the cognitive processes thought to underlie event segmentation. By tracking the shift from conventional stimuli to the capture of natural and more immersive experiences, the paper highlights the growing importance of creating experimental setups that closely mimic the most relevant features of real-world experiences to enhance ecological validity. Finally, we discussed how the gap between laboratory settings and naturalistic settings could be bridged by combining extended realities and mobile brain recording techniques.

Key takeaways from the paper

Based on the ideas we presented in sections 4, 5, and 6, we present some guidelines to help researchers design ecologically valid studies:

1. **Complexity:** Identify whether the cognitive process being investigated involves a few fundamental computations or more complex, multiple interacting higher-order processes.
2. **Task design:** Ensure that the task closely resembles the fundamental characteristics of the demands placed on the cognitive process in the situations encountered in the real world. For instance, it is possible that event segmentation occurs simultaneously and implicitly at various timescales in the real world, but most current studies employ intentional memory encoding paradigms with abrupt event changes. To obtain ecologically valid insights about the neurocognitive mechanisms underlying event segmentation, task designs involving smooth event transitions at multiple timescales and incidental memory encoding conditions may be necessary.
3. **Selecting stimuli:** The key question to consider is whether the selected stimuli effectively engage the intended processes as they would in real-world settings. Synthetic stimuli may suffice for studying simpler cognitive processes, but for more complex, interactive processes, the stimuli should be as naturalistic as possible along the dimensions most relevant to the cognitive processes under study.
4. **Providing contextual information:** When investigating complex cognitive phenomena in the lab, include contextual information that is typically associated with memory retrieval in natural settings because complex processes are especially context-sensitive. Take into account factors such as environmental cues, emotional context, or personal significance, as they can significantly influence memory processes in real-life situations.
5. **Participant Engagement:** Use immersive technologies, simulations, interactive tasks, or real-life scenarios to enhance participants' involvement and make the study environment engaging in contrast to the laboratory tasks that are repetitive and tedious. Participants often disengage from tasks that contain artificial stimuli that do not motivate them enough to stay on-task, (Seli et al., 2019) leading to reports of mind wandering.

CRediT authorship contribution statement

Raju Pooja: Writing – original draft, Investigation. **Pritha Ghosh:** Writing – original draft, Visualization. **Vishnu Sreekumar:** Writing – review & editing, Supervision, Conceptualization.

Data availability

No data was used for the research described in the article.

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