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Incorporating Ecological Momentary Assessment Into Multimethod Investigations of Cognitive Aging: Promise and Practical Considerations

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Ecological momentary assessment (EMA) represents a promising approach to study cognitive aging. In contrast to laboratory-based studies, EMA involves the repeated sampling of experiences in daily life contexts, enabling investigators to gain access to dynamic processes (e.g., situational contexts, intraindividual variability) that are likely to strongly contribute to aging and age-related change across the adult life-span. As such, EMA approaches complement the prevailing research methods in the field of cognitive aging (e.g., laboratory-based paradigms, neuroimaging), while also providing the opportunity to replicate and extend findings from the laboratory in more naturalistic contexts. Following an overview of the methodological and conceptual strengths of EMA approaches in cognitive aging research, we discuss best practices for researchers interested in implementing EMA studies. A key goal is to highlight the tremendous potential for combining EMA methods with other laboratory-based approaches, in order to increase the robustness, replicability, and real-world implications of research findings in the field of cognitive aging.

Keywords: ecological momentary assessment (EMA), cognitive aging, replicability, open science

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Research on cognitive aging has identified a diverse set of behavioral changes that take place as individuals grow older. A key goal for the field is to develop a unified account that can explain these changes in terms of their relevant mechanisms. This goal is a challenging one, given the accumulating evidence demonstrating considerable heterogeneity both across individuals and situational contexts in the degree to which cognitive processes change across adulthood (Salthouse, 2010; Stine-Morrow, 2007). The heightened awareness toward this heterogeneity has prompted researchers to use a variety of approaches to better characterize the processes underlying age-related changes in this domain, including longitudinal and sequential designs (Schaie, 2005), advanced statistical approaches (Hertzog & Nesselroade, 2003; Lakens et al., 2020; Lindenberger & Pötter, 1998), neuroimaging methods (Grady, 2008), and the identification of contextual factors that accompany aging (e.g., lifestyle features, motivation; Hess, 2014; Parisi et al., 2009; Reuter-Lorenz & Park, 2014). Likewise, recent years have seen a growing interest in characterizing intraindividual effects, to be able to better disentangle intra and interindividual sources of variability, and more fully understand the processes contributing to age-related cognitive changes (e.g., Nesselroade & Salthouse, 2004; Stawski et al., 2013).

Nevertheless, a shortcoming of these current research approaches is that there have been insufficient efforts to translate these laboratory-based findings into the daily lives of older adults, and even fewer attempts to bridge across multiple methods using naturalistic approaches. Thus, an important challenge for the study of cognitive aging is to integrate tightly controlled laboratory approaches with daily life assessments, as these latter methods may be able to better capture the complex environments and time-scales from which aging and age-related change unfolds. As such, the current paper aims to provide a methodological framework for cognitive aging researchers interested in incorporating intensive longitudinal measures of daily life into their existing programs of research. In particular, we emphasize the value of combining laboratory-based studies with daily life sampling approaches using rigorous and transparent research practices. This integrative, multimethod approach provides the unique opportunity to ask questions about the contexts and situations that define typical laboratory-based measures, while contributing to the open and replicable science of cognitive aging.

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Advantages of Daily Life Methods for Cognitive Aging Research

Even though there still remains a paucity of work using multimethod approaches to study cognitive aging in daily life contexts, the benefits of complementing laboratory-based methods with naturalistic assessments of thoughts and behavior have long been recognized. Broadly speaking, the use of multimethod approaches to index psychological processes is well-supported theoretically (i.e., multitrait, multimethod matrix; Campbell & Fiske, 1959). More specifically, life-span developmental theory has underscored the need to have *both* experimental control and real-world relevance when studying aging and age-related change (Baltes & Carstensen, 1996; Baltes et al., 2007; Bronfenbrenner, 1977; Li, 2003). Recent work has refined these theoretical frameworks, illustrating the importance of investigating developmental phenomena across diverse contexts (Arnett et al., 2020; Drewelies et al., 2019; Wahl & Gerstorf, 2018) and timescales (Gerstorf et al., 2014) in order to provide detailed explanations of the processes underlying adult development and aging. Nevertheless, within the domain of cognitive aging, the call to action put forth by these theoretical accounts, which encourages investigators to include assessments from both the laboratory and daily life, has largely failed to materialize.

Fortuitously, ecological momentary assessment (EMA) has emerged as a promising research approach to realize the measurement of adult developmental phenomena in daily life contexts (Brose & Ebner-Priemer, 2015; Cain et al., 2009; Hoppmann & Riediger, 2009). When used in conjunction with laboratory-based methods, EMA is an especially powerful tool to rigorously characterize cognitive aging across the adult life-span. To clarify, EMA is not a single research method, but rather, it is an umbrella term used to describe a diverse set of approaches that use the repeated collection of real-time (or close to real-time) data on participants' behavior and experience as it occurs in their natural environments (Shiffman et al., 2008). Put another way, EMA is characterized by three main features: (a) the ability to capture thoughts, feelings, behaviors, contexts (e.g., location), and physiological states (e.g., heart rate) that occur in participants' daily life environments, (b) intensive sampling of daily life experiences, resulting in many measurements over a relatively short time span (e.g., hours, days), and (c) the sampling of experiences in the moment of their occurrence, or shortly thereafter (Mehl & Conner, 2012). Conversely, it is important to point out that EMA studies do not preclude the use of experimental tasks or manipulations to assess participant behavior and cognitive performance. Even though EMA studies are most frequently employed as observational studies (e.g, using short surveys or passive collection methods), there is nothing in principle that prevents cognitive aging researchers from exporting the same tasks that are typically used in laboratory studies to more naturalistic contexts. In other words, the defining characteristics of an EMA study relate to how the dependent variables are acquired and measured, rather than how the independent variables are structured. Although there have been many terms invoked to describe methods of sampling participants' thoughts, feelings, or behaviors in daily life, such as Experience Sampling Methods (ESM; Csikszentmihalyi & Larson, 2014), Ambulatory Assessment (AA; Trull & Ebner-Priemer, 2013), and daily diary methods (e.g., Bolger et al., 2003), for the purposes of this review, we will use the term EMA.

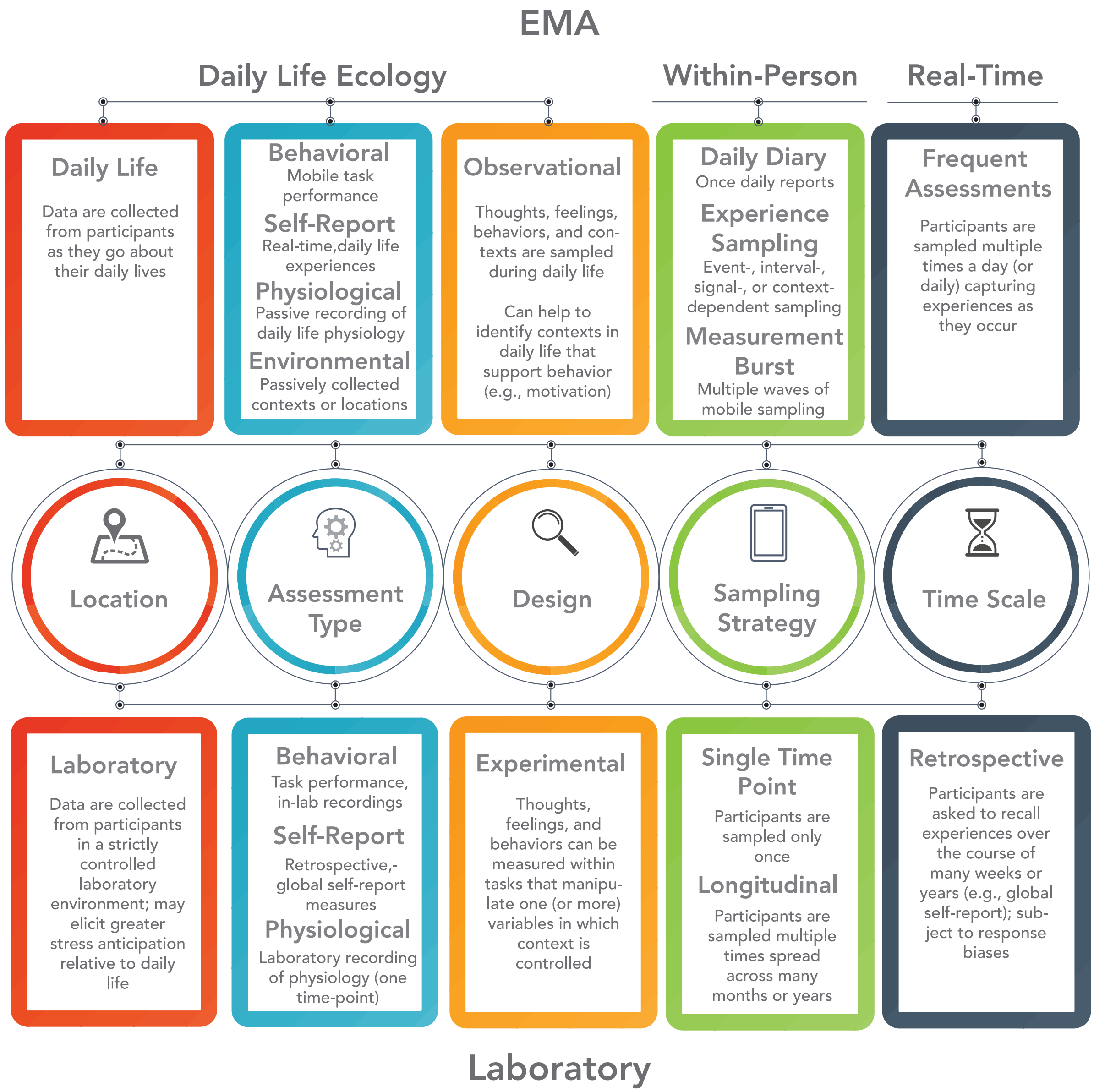
Daily Life Ecology

As described above, the primary defining feature of EMA is that it enables the assessment of psychological phenomena in daily life contexts, providing the means to extend our understanding of cognitive aging beyond the laboratory. In other words, EMA captures the environments and situations that participants are faced with as they move through the world. Thus, a clear advantage of using EMA to study cognition in older adults is the ability to measure cognitive phenomena outside of the laboratory context, where up until this point, the large majority of work characterizing cognitive aging has taken place (for further comparisons, see Figure 1). Indeed, prior work has shown that age differences in cognitive function may be exaggerated when the testing environment (i.e., laboratory) elicits greater arousal or stress anticipation, relative to other contexts (Hyun et al., 2019; Riediger et al., 2014). Accordingly, this disconnect has driven researchers to begin attempts to more frequently index cognitive phenomena outside of the laboratory.

An example illustrating the unique perspective that can occur when cognitive aging research is taken outside of the laboratory comes from research on mind-wandering. Currently, there is a strong foundation of laboratory-based investigation in this domain that suggests that older adults exhibit less mind-wandering than their younger counterparts (Maillet & Schacter, 2016). However, some researchers have speculated that contextual features, such as the stress of the laboratory environment, could contribute to these effects (McVay et al., 2013); yet, testing of such hypotheses has been limited by the use of primarily laboratory-based assessments. Fortunately, the emergence of EMA has made the study of mind-wandering in daily life a possibility. In fact, results from a recent EMA study have revealed that older adults also show less mind-wandering, even in daily life contexts, relative to younger adults, with systemic differences in the content of mind-wandering episodes (Maillet et al., 2018). Such studies serve to highlight the unique potential of EMA, relative to laboratory-based methods, by showcasing its power to quantify the behaviors of daily life across a wide variety of situations. Put another way, EMA provides researchers with the means to directly examine the stable constructs typically measured in the laboratory as they unfold in daily life, in addition to characterizing the contextual features that support such behaviors, thus further advancing our understanding of cognitive phenomena across the adult life-span.

Likewise, the rich sampling of daily life experiences afforded by EMA makes it an ideal tool to replicate laboratory-based findings in the more ecologically valid contexts observed in daily life. In particular, using the combination of both EMA and laboratory measures within-subject, it is possible for researchers to attempt to extend laboratory-based measures to daily life contexts, by testing whether critical findings and phenomena replicate within these contexts, and/or examining linkages (i.e., associations) across these domains. Indeed, others have suggested that EMA is an ideal technique to evaluate the external validity of laboratory-based findings (Schwarz, 2007). This may hold even greater importance when studying cognitive aging, since many aspects of older adults' daily life functioning appear to remain intact, despite a host of laboratory-based findings that suggest robust age-related declines across many metrics of cognitive function (Salthouse, 2012). As such, EMA provides the affordances for measuring "typical performance" in conjunction with relevant variables of daily life, such as affect and

Figure 1
Major Dimensions Through Which Laboratory and EMA Measures Differ



Note. Not all special cases are covered (e.g., laboratory measures could be sampled in a daily manner and EMA studies can utilize experimental manipulations); instead, the figure represents the most common uses of each type of assessment. EMA = ecological momentary assessment.

motivation, which will be critical for uncovering the mechanisms that support cognitive function in older adults.

As another example that highlights this issue, there have been mixed findings from laboratory-based research on prospective memory and aging, even though a number of studies demonstrate clear age-related decreases in prospective memory (Henry et al., 2004). In contrast, recent work using EMA has shown that, relative to younger adults, older adults actually engage in prospective memory more frequently in daily life (Gardner & Ascoli, 2015). This disconnect between findings from these different modalities suggests that older adults may show exaggerated decrements in prospective memory in laboratory-based environments, relative to daily life contexts. Although future work will need to more rigorously examine whether and how context (e.g., location of data collection) shapes prospective memory across adulthood, this example highlights the potential of using both EMA and laboratory approaches to promote replicability and discovery in cognitive aging research.

Furthermore, advances in mobile technology now provide unprecedented access into participants' daily life environments.

These advances present an exciting opportunity to expand our understanding of cognitive aging through the use of passively sampled EMA methods. Widely available wearable sensors and mobile sensing technology now enable researchers to collect passively sampled data with relative ease, indexing additional contexts (e.g., locations, with global positioning systems; GPS), auditory environments [e.g., with electronically activated recorder (EAR); Mehl, 2017], or physiological states (e.g., heart rate), in conjunction with self-reported thoughts, feelings or behaviors in daily life. Indeed, many researchers have recognized the tremendous potential in combining EMA with passive ambulatory monitoring to examine the linkages between participants' experiences and contexts (Kubiak & Smyth, 2019; Trull & Ebner-Priemer, 2014). Likewise, recent work has demonstrated the feasibility of using passive sampling techniques, such as the EAR, in studies of cognitive aging, highlighting the rich sources of information that auditory information can provide to our understanding of cognitive phenomena (e.g., memory, language) across a variety of contexts in daily life (Demiray et al., 2020).

The use of passive sampling techniques in EMA studies in cognitive aging research is just beginning, but there are many possible future directions that hold great potential. As just one example, if participants were given short cognitive assessments of working memory while audio is passively sampled from their mobile device, it would enable researchers to quantify the levels of ambient noise present in the environment, helping to uncover how this impacts task performance. In addition, there is likely to be other more detailed information present in the audio snippets that could indicate the source of potential distractions (e.g., spouse asks participant a question, doorbell rings). This type of contextual detail could be highly informative in enabling quantification of relevant features of the environment that contribute to working memory performance. Furthermore, experimental approaches can also be fruitfully combined with EMA in randomized controlled trials, allowing experimenters to better tease apart causal effects using intensive longitudinal measures (e.g., Schmiedek & Neubauer, 2020). For example, previous work has shown that older adults assigned to participate in an immersive volunteering experience had greater amounts of physical activity relative to controls not only during, but even after the intervention ended, as assessed via accelerometry (Varma et al., 2016). Thus, passive ambulatory monitoring technology has the potential to be productively paired with EMA to provide further insight into the naturalistic contexts and key features of daily life that contribute to our understanding of cognitive aging.

Within-Person Measurement

Another critical aspect of EMA that distinguishes it from most laboratory-based approaches in cognitive aging, is that it utilizes *the repeated sampling* of time points within participants in the context of their daily lives. As such, EMA is a highly sensitive technique, providing investigators with the means to assess important dynamic properties (e.g., contextual, temporal) that could contribute to cognitive functioning in older adults. By contrast, the typical laboratory-based approach attempts to describe age-related change based on cross-sectional comparisons, using data collected at a single time point, or in the case of longitudinal studies, within individuals, but spaced across relatively long temporal intervals (e.g., years). Although these laboratory approaches have provided important insights to our understanding of cognitive aging, they are fundamentally limited because interindividual differences, and intraindividual changes across the span of many years, do not necessarily translate into intraindividual change on a more granular timescale (e.g., days, weeks, months; Stawski et al., 2013).

It is important to recognize the subtle distinctions that are still present between EMA and laboratory-based studies, even when considering the special case of designs that utilize a microlongitudinal assessment approach (i.e., testing participants at frequent intervals in the laboratory over a relatively short time period). The value of laboratory-based, microlongitudinal studies in cognitive aging research has already been recognized for the important insights that they can provide (Gerstorf et al., 2014; Stawski et al., 2013). For example, more pronounced short-term fluctuations in cognitive ability measured in the laboratory have been associated with later cognitive declines in older adulthood (Lövdén et al., 2007).

Yet a critical distinction between laboratory-based, microlongitudinal and EMA approaches, can be seen in the situational contexts during which the assessments are made. With EMA, participants are sampled remotely, multiple times a day (or daily), over the course of many days, as they go about their daily lives. In contrast, laboratory-based microlongitudinal designs require participants to come to the laboratory for each assessment, in some cases, up to a total of 100 different occasions (e.g., Brose et al., 2010); this can greatly increase participant burden, relative to EMA studies, where participants are still subjected to repeated assessments, but are not required to travel into the laboratory each time to complete the assessment (i.e., EMA is completed in participants' natural environments, thus does not require additional travel). As a consequence, such approaches could inadvertently select for nonrepresentative participant populations. Moreover, laboratory-based microlongitudinal designs do not provide any assessment of the situational factors that might impact the psychological phenomena at the center of the research. In other words, by limiting participation to the laboratory, these designs fail to capture the complexities that could shape participants' experiences when performing the same task in daily life (e.g., fatigue, distraction, environment). In contrast, EMA provides researchers the tools to identify and quantify these dynamic properties in daily life (e.g., temporal, contextual). These tools and quantitative metrics can further help to adjudicate potential mismatch(es) that may arise when comparing measures from the laboratory and daily life, contributing to a more cumulative understanding of cognitive aging.

Furthermore, EMA designs enable the researcher to extend the time window of the sampling to include short measurement bursts over the course of several months (or years) to better understand how changes on the micro timescale (e.g., hours, days) translate to age-related changes over the span of many months or years. These types of designs will be critical in examining the interplay of time-varying factors that contribute to cognitive aging (for further discussion, see Gerstorf et al., 2014). Indeed, recent work has begun to provide support for the utility of employing multitimescale investigations (i.e., measurement burst designs) in adult life-span studies. For instance, short-term changes in cognitive performance and cardiovascular lability have been linked with better cognitive aging over a 13-year span (Ram, et al., 2011). As such, by extending cognitive aging studies into EMA-based measurement burst designs that characterize developmental phenomena across multiple levels and timescales, researchers will have exciting new opportunities from which to promote replicability and discovery in this research domain.

Constructs Measured in Real-Time

In the context of cognitive aging research, another important advantage of EMA is that it assesses experiences as they occur, or close to their occurrence, which can significantly reduce retrospective response biases. Global self-report measures, in contrast to many EMA-based methods, often require participants to reconstruct past thoughts, feelings, and behaviors, which may lead them to use a variety of strategies that are prone to systematic biases (Bradburn et al., 1987). Indeed, retrospective self-report measures appear to be more vulnerable to such response biases than momentary ratings indexed via EMA (Barrett et al., 1998). These biases may be especially problematic for older adults. In particular, retrospective responses biases have been shown to be more pronounced in older adults with declines in fluid cognitive functioning (Klumb & Baltes, 1999). Older adults are also susceptible to positivity biases in the recall of emotional information (Neubauer et al., 2020). Consequently, using methods that enable researchers to minimize these potential sources of error when surveying aging populations is of great importance.

Limitations of Daily Life Sampling Approaches in Cognitive Aging Research

Despite its many advantages, EMA does not come without challenges or obstacles. In the following section we highlight several areas that merit additional consideration from researchers interested in incorporating EMA into their work, as a part of a multimethod framework used to study cognitive aging. The following discussion is by no means exhaustive (for further discussion, see Carpenter et al., 2016; Conner & Lehman, 2012), but rather, our aim is to provide a well-rounded perspective on EMA as a tool for psychological inquiry in adult life-span samples, for those considering the adoption of the method into their own work.

Participant Burden

The burden for participants (e.g., commitment of time and effort) is often substantial when conducting an EMA study. In particular, EMA studies require participants to respond daily, or even several times a day, to surveys or short tasks, over the course of many days or weeks, in order to report about their thoughts, feelings, or behaviors in daily life. Furthermore, depending on the particular study design, participants may be asked to wear (and remember to charge) mobile sensing devices (e.g., heart rate monitors) in addition to completing the questionnaires in the EMA protocol. As such, EMA studies present a high threshold of engagement relative to other methods used in cognitive aging research, such as one-time laboratory assessments.

Despite the high levels of participant burden imposed by EMA studies, researchers have many potential strategies at their disposal that can help to lessen this burden on participants. For instance, researchers can take efforts to reduce the number of participant-generated response items (e.g., text entry) in the EMA surveys or tasks, and instead opt for multiple choice or sliding scale responses. In addition, when designing the study, researchers can be mindful of the trade-off between the quantity of items needed to assess the construct of interest, with how taxing the number of items will be for participants to complete on multiple occasions. Researchers can also take on some of the additional burden themselves, by implementing monitoring protocols that ensure participants are completing the majority of the EMA prompts, and that any external devices needed to complete the protocol (e.g., phone, passive monitoring) are functional while participants are using them, with further interventions in place to fix the technology, if the need arises.

Furthermore, participant compliance is another potential challenge associated with EMA utilization, which goes hand-in-hand with participant burden. Once the details of the EMA protocol are in place, it is strongly encouraged that research teams develop a thorough training protocol that can provide comprehensive instructions to the participants on how to use the sampling devices and complete the EMA protocol. This will help to set concrete expectations for the participants about what is required of them, and what the EMA protocol entails. Training is crucial not only for obtaining high rates of compliance and reducing participant burden, but also for acquiring high-quality data. As such, this issue merits serious consideration when deciding to conduct an EMA study (Conner & Lehman, 2012). Likewise, researchers can help to further bolster compliance and help to reduce participant burden by offering incentives for survey (or task) completion. This can be accomplished in a variety of ways, including paying participants for each completed response, by offering bonuses for completing a high proportion of responses (e.g., 80%), or by informing participants that they will be entered into a lottery if they complete a prespecified portion of responses. Prior work has shown that incentives are an effective strategy to improve compliance and maintain motivation throughout the sampling period (Musthag et al., 2011).

Missing Data

Although it is inevitable that there will be missing data when using EMA, given the intensive, longitudinal nature of the method, it is important to determine whether the data are missing systematically. For example, it is advisable to check for trends in completion rate both across- and within-days of the study protocol, as prior work has shown that compliance tends to decrease over the course of a study and in the early morning hours (Rintala et al., 2019). Furthermore, researchers conducting life-span studies will want to examine completion rates across age groups, to ensure that missingness does not vary in a manner that interacts with age. Fortunately, recent work has shown that, at least in college-aged participants, EMA data do not systematically vary in missingness across a wide variety of contexts (e.g., socializing, being engaged in mentally demanding tasks; Sun et al., 2020). However, these findings are not necessarily generalizable to certain types of EMA studies (e.g., those conducted with randomized signaling, in which assessments come at unpredictable times during the day), or with participant populations that span across adulthood, so close examination of missingness is still merited.

Nonetheless, even if the data are not biased by systematically missing data, high levels of missingness can still affect statistical power, given the limited number of observations. Thus, it is most prudent for researchers to plan ahead when determining the number of items and participants in an EMA study, anticipating some base-rate of missed responses across participants and some attrition due the lack of compliance with the protocol. To reduce the effects of missingness on statistical power, researchers are encouraged to employ multiple imputation methods on their intensive longitudinal data, which should improve the ability to test hypotheses (Graham, 2009; Ji et al., 2018). Nevertheless, the best strategy to mitigate the effects of missing data in EMA studies is a proactive approach, aimed at maintaining high rates of participant compliance (Palmier-Claus et al., 2011). Researchers aspiring to maximize participant compliance can use a range of strategies, including those discussed above, to help to provide high-quality EMA data and adequately powered studies.

Reactivity Effects

Another potential problem in using EMA involves reactivity effects. Reactivity effects arise when the method used to collect the data causes the phenomenon that is being measured (e.g., thoughts, feelings, behaviors) to change as a result of the sampling method (Scollon et al., 2003). Although, reactivity effects are a general problem that most researchers interested in the study of human behavior face, the nature of EMA designs (e.g., repeatedly assessing behavior in relatively short intervals) might exaggerate this problem, by inducing participants to pay more attention to their thoughts, feelings, or behaviors than they otherwise would have. For example, repeatedly asking older adult participants about whether they participated in cognitively demanding activities could actually have an influence on their daily routines, by increasing the frequency of these activities in later parts of the study period. Although there is not strong evidence to indicate that reactivity effects are a general problem for EMA studies (Barta et al., 2012; Stone et al., 2003), the nature of these effects could depend on the specific aspects of the study (e.g., content, sampling schemes, individuals), and could plausibly be more pernicious in cognitive domains (for which so far there is less data). As such, it is important to consider the possibility of reactivity effects when using EMA as a part of a multimethod framework to study cognitive aging.

Reduced Experimental Control

Even though the potential ecological validity afforded by EMA is one of its greatest strengths, daily life sampling comes at the expense of the external control researchers have over data collection. In contrast to laboratory-based approaches, in which researchers ensure tight control over most of the external factors to which participants might be exposed as they perform experiments or answer surveys, EMA approaches take place "in the wild" (i.e., the environments in which participants are currently situated). As such, these differing environments can be host to a variety of distractions (e.g., socializing with a friend, tending to a child) that affect participant compliance and diligence when completing assessments. Nevertheless, there are safeguards that researchers can implement to protect against poor quality data, including the close monitoring of participant compliance (Hoppmann & Riediger, 2009). For example, researchers can ensure that participants receive notifications on their mobile devices when they need to complete a survey and provide time limits (e.g., a 30-min window) for completing the survey, with built-in reminders if the survey has yet to be completed. Furthermore, the time taken to complete each survey can be summarized and if a particular response does not seem feasible (e.g., 20-second completion time for a 4-min average length survey), those responses can be flagged and potentially discarded for further analyses.

A key advantage to including EMA as a part of a multimethod approach to study cognitive aging is that it gives researchers the ability to capitalize on the relative strengths of each method, minimizing potential concerns about other methodological weaknesses present in their approach. In particular, the combination of both laboratory-based and EMA approaches provides the opportunity for strict experimental control in the laboratory environment, while also sampling of a variety of contexts in daily life, albeit in a less-controlled fashion. Accordingly, researchers can make decisions about the particular assessments that require a high degree of external control and assign those to laboratory testing, using EMA to instead study the phenomenon of interest with less experimental control, but more coverage across diverse situations and contexts in daily life. For example, a researcher interested in cognitive effort-based decision-making might decide to use the strict control of the laboratory setting to both assess cognitive function across a variety of domains, and to also have participants perform a decision-making task that indexes their subjective preferences related to cognitive effort (e.g., Cognitive Effort Discounting Task or Demand Selection Task; Kool et al., 2010; Westbrook et al., 2013). This would provide the researcher with precise estimates of participants' cognitive abilities and decision preferences, but leaves them with little understanding of how this decision-making extends beyond the laboratory and what contextual factors might influence participants' decisions. Although the researcher loses some of the control they had in the laboratory testing environment when using EMA, they stand to gain a considerable amount of knowledge about the frequency, content and diversity of activities participants are completing across a variety of daily life contexts, which nicely complements the data acquired from the laboratory.

Aging-Specific Concerns

Some might question whether mobile assessment tools are even a viable approach to study aging populations given the increased likelihood of functional limitations; however, such concerns are unfounded. Studies of older adults using EMA have been conducted for decades, even before modern technology enabled easier usage (Cain et al., 2009). Further, prior work has shown that older adults actually prefer being sampled via electronic devices, relative to filling out pen and paper questionnaires (Gwaltney et al., 2008) and are generally open toward using mobile technology in daily life (Kuerbis et al., 2017). Moreover, some EMA studies have reported higher rates of compliance in older, relative to younger adults (e.g., Livingstone & Isaacowitz, 2019; Rintala et al., 2019). Nevertheless, it is important to consider the unique challenges presented to researchers when conducting EMA studies across the adult life-span, especially if the populations being assessed have more severe functional limitations (e.g., >80 years old, mild cognitive impairment).

Despite the increasing prevalence of older adults with mobile phones (Kuerbis et al., 2017), EMA protocols may require participants to use their mobile devices in ways that are different from their everyday use. For example, participants might receive alerts from applications that they are not familiar with (e.g., from a 3rd party application), need to navigate a new interface in order to respond to questionnaires, or ensure that additional devices (e.g., heart rate monitors) are synching with their mobile device. Indeed, we suggest that researchers take great care to find a device and survey platform that is appropriate for a diverse age range to ensure that the characteristics of the survey (e.g., font size, signal loudness, ease of use) are suitable for participants of all ages. Further, it is advisable to set-up shortcuts on whatever mobile device is being used, and to provide participants with quick and easy ways to contact to study personnel, if the need arises. Thus, if possible, we recommend that all participants use the same type of device when completing an EMA protocol. Nevertheless, we realize that this could bring added expenses related to purchasing the mobile devices, and additional time costs involved with training participants on how to use them, as well as requiring participants to carry around an additional device. However, taking the time to address these potential device complications from the start will likely help to reduce participant burden during data collection. In general, the key objective is to make it as easy as possible for participants to follow the designed EMA protocol, resulting in better compliance and higher quality data.

Furthermore, potential age differences in daily waking and sleeping hours need to be accounted for when designing an EMA study. Regardless of the particular sampling design, it is recommended that all participants have the same size sampling window (e.g., 12 hr); however, the exact timing of this window can vary flexibly across participants to match their normal waking hours (Riediger & Rauers, 2018). Indeed, this participant-specific approach is ideal for investigations of cognitive aging, since waking hours and time-of-day effects are likely to vary substantially across different life stages (e.g., Anderson et al., 2014; West et al., 2002). If ignored, researchers could introduce unwanted confounds into their data; as such, it is advisable to query participants about their average waking and sleeping hours in order to reduce the likelihood of systematic missingness in the EMA data.

Despite the unique methodological challenges and complications associated with EMA, it is our view that the benefits often far outweigh the costs. Thus, EMA should be considered a promising and integral component of the methodological toolbox researchers can use to study cognitive aging. EMA offers an exciting opportunity to complement and expand our understanding of cognitive aging far beyond what can be learned from laboratory research alone. In addition, the barrier to entry to EMA research is lower than ever before; researchers interested in adopting EMA into their own work can now take advantage of a wide variety of openly accessible tools used to aide in the design, implementation, and analysis of EMA-based studies (e.g., preregistration templates, analysis pipelines; see Supplemental Materials). Moreover, the combination of EMA with fine-grained laboratory-based assessments and/or physiological/neural measures (e.g., pupillometry, heart rate, electroencephalography, fMRI) provides an exciting opportunity to bridge across multiple levels of analysis to elucidate the precise mechanisms that underlie changes in cognition across the adult life-span.

Ecological Momentary Assessment As a Tool for an Open and Replicable Science of Cognitive Aging

In this section, we synthesize the preceding review with a focus on implementing best practices in EMA research across the adult life-span, in order to facilitate the transparent dissemination of this work to the broader research community. Although our focus is on integrating EMA with other common approaches used to study cognitive aging (e.g., laboratory paradigms, neuroimaging), much of the discussion applies more generally to any EMA study, and as such should be adopted as part of the effort to build a transparent and replicable study of adult development and aging (see Table 1).

Reliability and Validity of EMA Measures

In contrast to laboratory-based research traditions, researchers using EMA face greater time limitations for each assessment. As a consequence, it is typically necessary to reduce the number of items used to assess the construct(s) of interest, relative to laboratory-based assessments. Unfortunately, there has been little work that has systematically examined the psychometrics of the truncated assessments often used in EMA studies (e.g., taking a subset of items from a larger subscale to fit within the time constraints imposed by EMA; for overview, see Shrout & Lane, 2012), and none to our knowledge in the context of adult life-span development. Nevertheless, there is a growing consensus that incorporating sound measurement practices into EMA-based research of adult development and aging is of critical importance and, as such, should not be taken lightly (Neubauer & Schmiedek, 2020). Accordingly, we highlight important issues pertaining to the psychometric properties of EMA

Table 1
EMA Best Practices and Their Contribution to Replicability (R), Transparency (T), and Discovery (D) in Cognitive Aging Research

Areas of contribution	Best practices	R	T	D
Measurement practices	• Identify which measures are reliable both within- and across-participants in daily life contexts (and across age groups)	✓	✓	✓
	• Quantify both reliability and validity, which are often not measured (or reported) in EMA studies		✓	
	• Develop psychometrically sound scales for EMA studies in adult life-span samples			✓
Reporting of results	• Describe, in detail, the experimental and analytical methods used (to facilitate replication attempts)	✓	✓	
	• Explain rationale for design and analytic choices		✓	✓
Preregistration	• Provide an honest accounting of what hypotheses were predicted prior to data collection, clearly distinguishing planned and exploratory analyses		✓	✓
	• Detail the methodological and analytic procedures to be used in the proposed study	✓	✓	

Note. EMA = ecological momentary assessment.

measures in order to help cognitive aging researchers in their efforts to contribute to methodologically rigorous investigations.

A key consideration for researchers interested in examining the reliability of the measures used in their study, is the recognition that items or tasks used in EMA surveys will index both between- and within-person variability. As such, it is important to consider not only the between-person reliability, but also the within-person reliability when evaluating the measurement properties of EMA study items (Calamia, 2019). Fortunately, the statistical tools used in the analysis of EMA data (e.g., multilevel modeling, structural equation modeling), are the same ones that researchers can use to calculate both between- and within-person reliability for their studies, by partitioning the between- and within-person variance for the variable(s) of interest over time. When using self-report measures with EMA, a useful guiding principle and recommendation is to use at least three items for each construct that is assessed (Carpenter et al., 2016; Nezlek, 2020; Shrout & Lane, 2012). Given the time constraints involved in assessing participants remotely via EMA, researchers should be aware that both between- and within-person reliability estimates will likely be lower relative to the same measures collected in the laboratory. Thus, researchers need to adopt a pragmatic approach, weighing the costs and benefits of the number of items and constructs assessed in order to strike a balance between sound measurement practices and participant burden. In the future, computerized adaptive testing approaches may provide a more precise way to assess constructs of interest over short time intervals (Germine et al., 2021), helping to improve the measurement phenomena of interest to cognitive aging researchers.

Researchers interested in adapting cognitive paradigms to daily life sampling may face additional challenges with regard to reliability. Much like the trimming of self-report measures to accommodate the reduced time for assessments with daily life sampling methods, researchers will likely need to reduce the number of trials in EMA studies, relative to what would be considered standard in traditional lab-based assessments of cognitive function. This trimming will also likely reduce the reliability of the cognitive measure. Furthermore, the repeated administration of cognitive tasks is known to contribute to practice effects, which impact both older and younger adults (Salthouse, 2010). However, much of the research on practice effects is limited to data collected in laboratory contexts at fewer time points (e.g., two or three times) and over much longer time intervals (e.g., days, weeks, months) than would be collected using EMA.

The current state of the field leaves researchers with very little data pertaining to the impact of repeated cognitive assessments collected frequently in daily life contexts (Calamia, 2019). Despite these potential challenges, recent findings have demonstrated the feasibility of collecting cognitive assessments with EMA across the adult life-span (Daniëls et al., 2020; Jongstra et al., 2017; Koo & Vizer, 2019; Lange & Süß, 2014). Notably, this work has shown that mobile cognitive assessments demonstrate reliable between- and within-person variability, with tasks of processing speed and working memory using far fewer trials than laboratory-based assessments of the same constructs (Sliwinski et al., 2018). Furthermore, other work has highlighted the additional promise of mobile cognitive assessment tools. For example, one provocative result indicated that, when aggregated within individuals across time, mobile cognitive assessments actually provided a more sensitive behavioral index, in terms of the strength of correlation with brain function, than a similar measure collected in the laboratory at one time point (Allard et al., 2014).

Furthermore, when considering issues of measurement, it is important to not neglect possible threats to validity when using EMA, despite the specific promise of this tool to provide greater ecological validity to the study of cognitive aging. In particular, many of the limitations of EMA (e.g., issues of compliance, potential for reactivity) can compromise the validity of the assessments. For example, if an EMA protocol has very low compliance, it will not be sampling from as wide of a variety of experiences from daily life, which will threaten the validity of the assessments. In addition, researchers should be careful not to select assessment items solely based on their reliability (e.g., taking a subset of highly similar items from a larger self-report scale), since this could result in poor representation of what the scale was originally intended to measure or fail to provide adequate coverage of the construct (Calamia, 2019). Further, even the analysis of EMA data also has the potential to compromise validity (Ram, et al., 2017). For example, data analysis is often performed in an aggregate manner whereby all observations across all participants are included in one model (e.g., multilevel model). This approach assumes that there is heterogeneity across observations and participants, which might not always be an accurate assumption (e.g., some participants might have no variability in their behaviors over time). As such, making this assumption could provide false conclusions about the ecological validity of the construct if adequate checks are not made to the data beforehand. Together, this highlights the careful considerations that researchers should take ranging from the design, implementation, and analysis of EMA studies when trying to optimize their measurement practices.

As just described, there are challenges for researchers in considering the psychometric properties of EMA measures. However, recent efforts have begun to lower the barrier for those interested in exploring these issues more deeply. For example, a growing consortium of researchers has begun to curate an online repository with items used in prior EMA studies (Kirtley et al., n.d.) with the aim of psychometrically validating these items. Although this resource is still in its early stages, it is an excellent place to begin to get a sense for the type and number of items used in prior work. Further, the repository provides researchers with the opportunity to contribute their own items into a growing pool of openly available resources. Such contributions will greatly aid the effort to develop psychometric validation of EMA measures used in cognitive aging research, of which there is currently very little investigation.

Transparent Reporting Practices

Despite the vast proliferation of EMA research over the past decade, there has been little consistency in the literature pertaining to the reporting of the design and methods used in these studies. For example, a recent review of published EMA results with adolescent samples found that the vast majority of studies did not provide critical details of the study design (e.g., number of items used, duration of questionnaire, power analyses) or data collection procedures (e.g., type of device, software, participant compensation; van Roekel et al., 2019). This pattern reflects the findings of a recent meta-analysis of reporting practices of EMA studies in the field of psychopathology, which also showed vast inconsistences in the reporting of aspects related to experimental design, data collection, and analysis (Trull & Ebner-Priemer, 2020). This work also highlighted some troubling consistencies in the reporting of EMA studies, with only 2% of the published work including any kind of a priori power analysis (Trull & Ebner-Priemer, 2020). Indeed, the lack of consistent and rigorous reporting practices for EMA studies presents a problem for replicability, and reveals some of the challenges awaiting researchers interested in adopting EMA into their own work.

In an effort to curtail inconsistencies in the ways in which EMA studies are reported, many have suggested that researchers adopt common reporting practices for studies using EMA. These efforts have focused on the pertinent, but often overlooked and omitted, details that should be included in publications using EMA, such as participant compliance, EMA software and device specifications, sampling designs, statistical power, and analytic approaches (van Roekel et al., 2019; Stone & Shiffman, 2002; Trull & Ebner-Priemer, 2020). For example, although many studies report overall rates of compliance, very seldom is compliance reported both at the level of the sample and the participant, which is an important consideration, especially for researchers interested in using similar methods in their own work. Fortunately, there are now clear and easy to use checklists and guidelines that researchers can consult when developing and reporting the results of their own EMA studies, significantly lowering the barrier for those interested in conducting this type of work (van Roekel et al., 2019; Trull & Ebner-Priemer, 2020). As the use of EMA continues to grow in the field of cognitive aging, and beyond, it will be critical for researchers to promote open and replicable approaches, by adopting these reporting practices in their work, which facilitate a clear and comprehensive description of both the rationale and pertinent details of the design and methods.

Preregistering Hypotheses

An additional important practice for promoting transparent and replicable research practices with EMA is for researchers to standardize their reporting *prior* to data collection, as well as after it. This can be most easily accomplished through the use of preregistration. As the field of psychology has grappled with various questionable research practices, such as HARKing (hypothesizing after results are known; Kerr, 1998) or publication biases, preregistration methods have been strongly advocated as an effective solution. Preregistration requires that the researchers conducting a study provide explicit documentation of the experimental design, sample characteristics (e.g., approximate sample size, stopping rules), and analytic methods prior to collecting (or analyzing, in the case of secondary data analysis) any data (Nosek et al., 2018). The preregistration is then uploaded to an openly available platform (e.g., Open Science Framework, AsPredicted) and is time-stamped and locked to prevent further editing. Thus, a preregistration provides a clear distinction as to which hypotheses were developed prior to data collection (or analysis), to distinguish these more clearly from posthoc and exploratory analyses, while also providing rich methodological detail about the proposed study. Given the lack of clear and rigorous reporting described above, preregistration of EMA studies provides an exciting opportunity to build a more transparent and replicable field of cognitive aging.

Indeed, there have been recent efforts to help researchers interested in conducting EMA studies use open science tools for study planning (see Supplemental Materials). In particular, there is now an openly available EMA-specific preregistration template with accompanying tutorial, which provides a clear and concise guide for other researchers interested in using EMA, with content areas significantly overlapping with the suggested reporting practices described above (Kirtley et al., 2021). In parallel, there have been efforts to make it easier to conduct the power analyses often needed for the complex data structures inherent to EMA. Those interested in using simulations to conduct power analyses for EMA studies can access a tutorial with accompanying Shiny app (Lafit et al., 2021), which significantly lowers the statistical and computational burden required to perform these analyses. Furthermore, it is important to take the number of observations and the reliability of the construct of interest into consideration when performing power analyses for EMA studies (e.g., Bolger & Laurenceau, 2013). Indeed, recent work highlights these considerations in adult life-span samples conducted with EMA, providing a strong basis for the feasibility of conducting well-powered EMA studies in the field of cognitive aging (Scott et al., 2020; Stawski et al., 2019). Together, these resources offer tremendous potential in helping to establish a rigorous and transparent foundation for future cognitive aging studies that adopt EMA approaches.

Nevertheless, EMA approaches are only a part of the methodological toolbox researchers can use when taking a multimethod approach to study cognitive aging. Accordingly, we would encourage all researchers interested in incorporating EMA into their research to use these recommended open science practices. Additionally, following the more general guidelines recently outlined for aging research (Isaacowitz & Lind, 2019) will provide a stronger foundation for empirical investigations. As such, we have created a preregistration template specific for those who wish to extend laboratory-based measures into daily life contexts using EMA with adult life-span samples (see Supplemental Materials). It is our hope that this template will serve as a launch point for others interested in incorporating EMA into their work while also adhering to recommended open science practices.

Conclusion

EMA has the potential to be a powerful tool in elucidating the mechanisms underlying cognitive changes across the adult life-span. Indeed, EMA has already contributed important findings to our understanding of cognitive aging, including how short-term changes in cognitive performance translate to healthy aging, over the course of many years (Ram, et al., 2011). Such findings will be essential to advancing our understanding of the processes that support healthy cognitive aging, in addition to identifying the mechanisms underlying age-related cognitive decline. Moreover, the technology to administer these assessments and the statistical tools to analyze them are already in place. Indeed, they have already been successfully applied in many recent EMA studies across the adult life-span. Nevertheless, there are still many untapped extensions in the field of cognitive aging that are ripe for experimentation with EMA. Importantly, EMA provides the means to replicate laboratory-based measures in daily life contexts, while also providing additional insights that laboratory-based measures cannot. In other words, the unique access EMA provides to daily life experiences and contexts is what sets it apart from other methods used to study processes that contribute to aging and cognition. Thus, EMA can provide an unparalleled methodological contribution to our understanding of the processes that support cognitive aging. Finally, the unique features of EMA position it as a powerful measurement tool that can meaningfully contribute to a more comprehensive and replicable understanding of cognitive aging, with a strong focus on extending our knowledge to daily life contexts.

It is important to appreciate that EMA is not a panacea—thoughtful considerations need to be taken to ensure that EMA is implemented in a sound and rigorous fashion to build upon prior work, and to provide parsimonious accounts of cognitive aging. Further, EMA studies need to be designed with diverse populations in mind (e.g., across the adult life-span, different exposure to technology). Our primary recommendation is to adopt the complementary utilization of both laboratory-based and EMA measures in order to build more extensive bridges between these two research approaches, providing researchers with a more complete view of cognitive aging. As such, it may be necessary to engage in extensive pilot testing before large-scale investigations can be realized. Yet when properly utilized, EMA represents a powerful conceptual and methodological tool that can elucidate critical factors and contexts associated with psychological constructs of interest. As such, particularly when implemented with the best practices described above, EMA approaches can become a central component of the effort to build a cumulative and transparent science of cognitive aging, using a multimethod framework.

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