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Outside of the Laboratory: Associations of Working-Memory Performance with Psychological and Physiological Arousal Vary with Age

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Abstract

We investigated age differences in associations between self-reported experiences of tense and energetic arousal, physiological activation indicated by heart rate, and working-memory performance in everyday life. The sample comprised 92 participants aged 14 to 83 years. Data were collected for 24 hours while participants pursued their normal daily routines. Participants wore an ambulatory bio-monitoring system that recorded their cardiac and physical activity. Using mobile phones as assessment devices, they also provided an average of seven assessments of their momentary experiences of tense arousal (feeling nervous) and energetic arousal (feeling wide-awake), and completed two trials of a well-practiced working-memory task. Experiences of higher energetic arousal were associated with higher heart rate in participants younger than 50 years of age, but not in participants older than that; and energetic arousal was unrelated to within-person fluctuations in working-memory performance. Experiences of tense arousal were associated with higher heart rate, independent of participants' age. Both tense arousal and physiological activation were accompanied by momentary impairments in working-memory performance in middle-aged and older adults, but not in younger individuals. Results suggest that psychological arousal experiences are associated with lower working-memory performance in middle-aged and older adults when they are accompanied by increased physiological activation, and that the same is true for physiological activation deriving from other influences. Age differences in cognitive performance may hence be exaggerated when the assessment situation itself elicits tense arousal or occurs in situations with higher physiological arousal arising from affective experiences, physical activity, or circadian rhythms.

Keywords: Ambulatory assessment, working memory, tense and energetic arousal, heart rate, age differences, experience sampling

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Daily life is replete with situations that require people to retain and update information in their minds for some time. The responsible mental faculty is commonly referred to as working memory (Baddeley, 2003). A central characteristic of working memory is its limited capacity. This becomes evident, for example, when distractions can leave one clueless as to the name of a person one has been introduced to only moments ago, or as to the topic of the conversation before an interruption. These limits in working memory also place constraints on how well one can perform more complex cognitive tasks, such as reading, planning, problem solving, or reasoning (e.g., Unsworth, Heitz, & Engle, 2005).

There is little controversy that age is a central determinant of working memory. Evidence abounds, for example, that older adults' performance in working-memory tasks assessed in laboratory contexts, on average, is lower than that of younger adults (for a review, see Sander, Lindenberger, & Werkle-Berger, 2012). Working-memory performance can however also vary within the same persons over time, being better on some occasions and worse on others (Brose, Schmiedek, Lövdén, & Lindenberger, 2012). Identifying contexts that allow older adults to fully exploit their working-memory potential can thus have important practical implications. Furthermore, if individuals from different age groups achieve maximal working-memory performance in different contexts, then age-group comparisons that do not consider the role of context will yield a limited and potentially distorted pattern of findings.

The present research investigated the assumption that the individual's momentary level of arousal represents a contextual factor that differentially affects working-memory performance in different age groups.

Psychological and Physiological Aspects of Arousal

Arousal is a state of heightened activation, responsiveness to sensory input, and readiness to act (Boehringer, Schwabe, & Schachinger, 2010). It is reflected in people's psychological experience as well as in their physiological activation, which, evolutionarily, has served to prepare them for adaptive behavioral responses, such as flight in the case of fear (cf. Hanoch & Vitouch, 2004).

Psychological experiences of arousal can be characterized by two types of activation: energetic arousal (ranging from feeling sleepy to feeling wide-awake) and tense arousal (ranging from feeling calm to feeling nervous; Thayer, 1996). Empirical evidence supports the distinctiveness of these dimensions of psychological arousal (Schimmack & Reisenzein, 2002). They are, for example, differentially related to external influences such as circadian rhythms (e.g., Jankowski & Ciarkowska, 2008), and can change in different directions within a given person (e.g., Gold, MacLeod, Deary, & Frier, 1995).

The physiological activation accompanying psychological experiences of arousal can vary across organ systems depending on the behavioral response called for, but characteristically involves an increase in heart rate. Heart-rate increases result from a rise in activating influences on the heart from the sympathetic nervous system, coupled with a withdrawal of calming influences from the parasympathetic nervous system (Burg & Pickering, 2011). Increased heart rate intensifies the energy supply to the brain and body and thus enhances the individual's preparedness to act (e.g., Bradley & Lang, 2000). We used naturally occurring fluctuations of heart rate, controlling for the respective influences of momentary physical activity, as an indicator of physiological activation accompanying psychological experiences for two reasons: Cardiac activity is a reliable and unspecific indicator of arousal that is involved in physiological activation patterns accompanying a broad range of psychological experiences (Kreibig, 2010), and high-quality long-term ambulatory monitoring of cardiac activity is feasible in daily life.

Arousal and Working Memory

The idea that arousal is associated with fluctuations in cognitive performance dates back to Yerkes and Dodson (1908). Today, many psychology textbooks impart generalizations of their work as the Yerkes-Dodson law. This law postulates that both too low and too high levels of arousal are detrimental to performance, and that the optimal level of arousal is lower the more difficult the task is (for review, see Hanoch & Vitouch, 2004).

As the underlying mechanism, various researchers have proposed that arousal affects cognitive performance through its effects on information processing (Easterbrook, 1959; Humphreys & Revelle, 1984; Mather & Sutherland, 2011). Easterbrook (1959), for example, proposed that heightened arousal leads to an increasingly narrow focus of attention. At optimal arousal levels, relevant information is attended to, whereas peripheral information is disregarded. Lower arousal is suboptimal because irrelevant and thus potentially distracting information is processed as well. Higher arousal is also suboptimal because the focus of attention is too narrow to process all relevant information. Optimal levels of arousal should thus depend on the amount of information that needs to be processed, but also on the attentional capacity of the individual. The smaller the individuals' attentional capacity is, the less information they can attend to at a given level of arousal. Narrowing the attention focus with increasing arousal should thus result in optimal information utilization at lower arousal intensities for individuals with smaller attentional capacity.

Evidence suggests that attentional capacity declines with age throughout adulthood (for a review, see Verhaeghen, 2011). It has also been argued that higher arousal is particularly costly for older adults (Charles, 2010). The close connection of attention processes and working-memory functions (Awh, Vogel, & Oh, 2006) gives rise to the assumption that older adults' working-memory performance should reach a maximum at a lower level of arousal than that of younger individuals.

Indirect support for this idea stems from investigations in other performance domains. Bäckman and Molander (1991), for example, investigated younger and older skilled miniature golf players. Younger and older players showed a comparable increase in self-reported anxiety (tense arousal) and heart rate between training and competition; however, whereas younger adults' performance improved in competitive play relative to training, older adults' performance deteriorated. Similarly, Hogan (2003) reported that higher self-reported anxiety (tense arousal) was associated with greater performance decrements in divided attention tasks in older adults than in younger adults.

The present study extended this line of research by investigating age differences in the association between naturally occurring fluctuations in psychological and physiological measures of arousal and working-memory performance in everyday life. Its purpose was to demonstrate that low arousal helps older adults more than other age groups to exploit their working-memory potential in everyday contexts. We also investigated whether tense arousal and energetic arousal may play different roles in this respect. The little available evidence suggests that tense arousal impairs older adults' performance more than it does younger individuals'. We are not aware of a study that investigated whether the same is true for energetic arousal. Previous research with young adults, however, found differential associations between cognitive functioning and tense versus energetic arousal. Whereas tense arousal can impair performance in highly demanding cognitive tasks, energetic arousal has been found to facilitate younger adults' cognitive performance in such situations (e.g., Matthews & Davies, 2001). We therefore hypothesized that it may be specifically tense (but not energetic) arousal that impairs older adults' everyday working-memory performance more than that of younger individuals.

Method

Participants

The sample comprised 92 participants ranging in age from 14.7 to 83.2 years (M = 42.4, SD = 19.0). All participants lived in Berlin, Germany, and had been recruited by a fieldwork agency in the context of a larger research project. The sample was approximately stratified by gender (45% men) and age (14–18 years: n = 10; 19–29 years: n = 18; 30–39 years: n = 16; 40–49 years: n = 14; 50–59 years: n = 12; 60–70 years: n = 15; 70–83 years: n = 7). Of the participants, 31.5% were married, 28.3% were unmarried but lived in a partnership, and 48.9% had one or more children. Most of the participants were either currently employed (47.8%) or attending school, vocational training, or university studies (26.1%). Of the participants, 14.1% held a university degree, 53.3% had completed vocational training, 23.9% had graduated from secondary school, and 8.7% had not yet graduated from secondary school. Twelve participants (13%) reported previous disorders of cardiac functioning. Electrocardiogram (ECG) data for two of these participants indicated current cardiac arrhythmia and were therefore excluded from analyses. ECG data for one additional participant were not available because of technical problems. The effective sample size for analyses involving physiological measures was therefore N = 89.

Procedure

Participants came to the laboratory where trained experimenters attached a portable biosignal recorder (Varioport from Becker Meditec) as well as ECG and acceleration sensors to the participants. ECG electrodes were placed on the thorax in the standard three-lead chest configuration *Goldberger avR* (Huppelsberg & Walter, 2005). A three-dimensional acceleration sensor was placed at the sternum and a one-dimensional acceleration sensor was attached to the right thigh.

Participants then returned to their daily lives for on average 25.8 hours (*SD* = 0.8 h, *min* = 22.3 h, *max* = 29.8 h), which started as they left the laboratory and continued until their return on the next day. During that time, ECG and accelerometry data were continuously recorded. In addition, participants carried mobile phones (Nokia E50) with them as assessment devices for the repeated measurement of, among other things, their momentary tense arousal, energetic arousal, working-memory performance, current type of type of activity, and social partner(s). Participants' gave informed consent. The ethics committee of the Max Planck Institute for Human Development approved the study.

Measures

Perceptual speed. The Symbol-Digit Test (Lang, Weiss, Stocker, & Rosenbladt, 2007) was used to investigate potential sample selectivity in cognitive capacity. This a modification of the Digit-Symbol Substitution Test (Wechsler, 1981) for computer-assisted assessment (Lang et al., 2007). Participants were given mappings of symbols and digits, and their task was to enter the corresponding digit for a presented symbol as fast as possible. The number of correct responses entered within 90 seconds served as an indicator of perceptual speed and was used as a person-level marker of general cognitive capacity. Age-graded performance norms are available from the representative German Socio-Economic Panel (SOEP, Wagner, Frick, & Schupp, 2007). An experimenter was present during assessment of performance, in a manner akin to laboratory studies.

Mobile-phone assessments. On each of the two study days, mobile-phone assessments were scheduled within a 12-hour time window chosen by the participants according to their personal waking habits, such that one assessment occurred within each of the six subsequent two-hour time periods. Each assessment started with a number of self-report questions. Following these, participants completed two trials of the working-memory tasks (see below). At the beginning of each mobile-phone assessment, at the beginning of each trial of the working-memory task, and at the end of each mobile-phone assessment, participants were instructed via the mobile-phone screen to press a button on a pen-like marker device that was connected to the biosignal recorder. This allowed the precise mapping of the physiological recordings and the mobile-phone assessments. On average, participants completed seven mobile-phone assessments, $SD = 0.8$, $r_{\text{age}} = .05$, $p = .31$, during the two-day study phase.

Self-reported tense and energetic arousal. During each mobile-phone assessment, participants reported their current tense arousal by indicating how nervous (German: nervös) they momentarily felt and their current energetic arousal by indicating how wide-awake (German: hellwach) they momentarily felt, using a scale ranging from 0 *"not at all"* to 6 *"very much."*

Current type of activity and social partner/s. Participants also indicated at each mobile-phone assessment their type of activity at the moment by checking appropriate response options. Responses were combined into *occupation* (work/school/study), *errands* (chores/errands and doctor or office visits), *leisure* (leisure activity, conversation/visit, and doing nothing/sleeping/watching TV), and *unspecified* (other and multiple categories chosen). Participants further indicated which other persons were present. Responses were combined into *alone*; *private acquaintance(s)* (partner, family, friends); *non-private acquaintance(s)* (colleagues/fellow pupils or students); *stranger(s)*; and *unspecified* (other and multiple categories chosen). Participants' momentary type of activity and social partner/s served as covariates in our control analyses (effect coding with unspecified as reference category).

Working-memory task. Following these self-reports, participants completed two trials of a numerical memory-updating task (Salthouse, Babcock, & Shaw, 1991). Prior to the present data collection, participants had practiced the task intensively in a previous study in which they had completed two trials during each of $M = 54.9$ testing occasions, $SD = 4.1$ (Riediger, Wrzus, Schmiedek, Wagner, & Lindenberger, 2011).[1] In each trial, four digits in a grid of two-by-two cells were simultaneously presented to participants for 6,000 ms. Then, five updating operations (additions and subtractions within a range of –8 to +8) appeared successively in the cells of the grid (presentation times 3,500 ms; ISI 500 ms) in a way that no digit was updated twice in a row. Intermediate and end results were all in the range of zero to nine. The participant's task was to enter the end results for each of the four cells. Performance feedback was provided. The percentage of correct responses across both trials served as an indicator of momentary working-memory performance. Thirteen (2.1%) univariate outliers ($|z| > 3$) with performance scores below 25% (that probably resulted from the guessing of responses) were excluded from analyses. Within-person variation in task performance was unrelated to participants' age ($r = -.14$, $p = .189$).

Analyses of potential cumulative and cyclic trends in working-memory performance. To examine whether cumulative or cyclic trends were observable in participants' working-memory performance, we ran two series of multilevel models predicting momentary working-memory performance. To identify potential cumulative trends, we compared the model fits of (a) a no-change (i.e., intercept-only) model that included no predictors, (b) a linear-change model that included occasion number, counting from zero, as a single fixed and random predictor, and (c) a quadratic-change model that additionally included the fixed squared term of occasion number as predictor (cf. Singer & Willet, 2003). Likelihood ratio tests on the change in deviance indicated that including linear or quadratic change as model predictors did not significantly improve the model fit compared to the no-change model; $\chi^2(\text{df} = 2) = 2.4$, $p = .301$ and $\chi^2(\text{df} = 3) = 2.5$, $p = .475$, respectively. There was thus no indication of a cumulative trend in working-memory performance throughout the $M = 7$ assessment occasions.

We followed the same rationale to examine potential cyclic trends in working-memory performance. Here, we compared the model fits of (a) an intercept-only model, (b) a linear time-of-day model in which time of day (centered at 6 am, the approximate time of the earliest assessment in this study) was included as a single fixed predictor, and (c) a quadratic time-of-day model that additionally included a fixed effect for squared time of day. Note that we removed the random effect for time of day from these analyses because the respective parameter estimate was not significant, and because removing the term did not change the overall model fit, $\chi^2(df = 1) = 0$, $p = 1$. Likelihood ratio tests on the change in deviance indicated that the quadratic time-of-day model fit the data better than the linear time-of-day model, $\chi^2(df = 1) = 4.4$, $p = .036$, and the intercept-only model, $\chi^2(df = 2) = 6.4$, $p = .041$. Parameter estimates (intercept: 88.831, *SE* = 3.076, $p < .001$; time of day: –1.345, *SE* = 0.778, $p = .084$; squared time of day: 0.098, *SE* = 0.046, $p = 0.035$) indicated a U-shaped circadian function of working-memory performance, which, however, was rather flat (1.35% within-person residual variance accounted for; model-predicted average working-memory performance at 6 a.m. = 88.83%, at 12 p.m. = 84.33%, at 6 p.m. = 87.03%). There was no indication of age-differences in this circadian trend (i.e., $p >.05$ for age interactions with the linear and quadratic time-of-day terms). To account for the slight cyclic trend in working-memory performance, we included the linear and squared effects of time of day in our control analyses.

Heart rate. The average heart rate during the quasi-standardized situation of responding to the self-report items immediately preceding the working-memory tasks served as the indicator of physiological activation. This avoided including physiological arousal due to the cognitive load of the working-memory task in our analyses. Examination of the heart rate distributions revealed the existence of three univariate outliers ($|z| > 3$), which were adjusted to the closest non-outlying value in the distribution.

Physical activity. An indicator of participants' average physical activity during the self-reports was determined using data from the two acceleration sensors attached to participants' sternum and right thigh (Fahrenberg, Foerster, Smeja, & Mueller, 1997; Mathie, Coster, Lovell, & Celler, 2004). After removing potential measurement-related drift (Hennighausen, Heil, & Rösler, 1993), absolute values of the data from both sensors were summed for the period during which participants responded to the self-report items and then divided by the duration of that time period. This yielded an indicator of participants' average whole-body physical activity per minute in the quasi-standardized situation immediately preceding the assessment of momentary working-memory capacity. These values were log-transformed to normalize the left-skewed distribution, which was due to the occurrence of more measurement occasions with little physical activity (for details, see Wrzus, Müller, Wagner, Lindenberger, & Riediger, 2013).

Multilevel Regression Analyses

All multilevel regression models reported in this paper were conducted in SAS PROC MIXED and used restricted maximum likelihood estimation and the spatial power residual covariance structure (an autoregressive structure that takes unequal spacing of measurement occasions into account, Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2007).

Results

Sample Selectivity

A comparison of the present participants' performance in the Symbol-Digit Test with that of their age peers in the 2006 assessment of the SOEP sample indicates that the present sample is sufficiently representative with regard to cognitive capacity. Only participants within the overlapping age ranges of both samples (i.e., 16.32 to 82.54 years of age) were included in this analysis (present sample: $N = 87$, SOEP sample: $N = 5{,}457$). A univariate analysis of variance with age group (<18, 18–29, 30–39, 40–49, 50–59, 60–70, 70+ years) and sample membership (present sample, SOEP) as between-person factors yielded a significant main effect for age group, $F(6, 905.81) = 11.20$, $p = .000$, partial $\eta^2 = .01$, indicating that psychomotor-speed performance was highest among young adults and declined into old age.[2] Neither the main effect of sample membership nor the Age Group × Sample Membership interaction reached statistical significance, $F(1, 149.33) = 1.85$, $p = .17$, partial eta squared = 0.000 and $F(6, 488.98) = 1.01$, $p = .42$, partial $\eta^2 = .001$, respectively, which is consistent with the view that the present participants were comparable to their German age peers with regard to Symbol-Digit performance.

Age Differences in Arousal

To investigate possible age differences in our measures of psychological arousal (tense, energetic) and physiological activation, we ran three multilevel regression analyses. Dependent variables were the arousal measures (self-reports of feeling wide-awake, feeling nervous, and heart rate while responding to self-report items). The independent variable was participants' age. We also included the squared term of participants' age to investigate potential non-linear age effects on arousal. Participants' age was not systematically related to how nervous participants reported feeling, on average (intercept $b = 0.551$, $SE = 0.112$, $b_{age} = 0.002$, $SE = 0.004$, $p = .652$, $b_{age\_squared} = 0.0002$, $SE = 0.0002$, $p > .301$). There were, however, significant age effects with regard to the other arousal measures: The older participants were, the more they tended to endorse feeling wide-awake, on average (intercept $b = 3.452$, $SE = 0.135$, $b_{age} = 0.018$, $SE = 0.005$, $p < .001$, $b_{age\_squared} = -0.0003$, $SE = 0.0003$, $p = .353$). Results further indicated an inverted U-shaped age effect on average heart rate (intercept $b = 84.115$, $SE = 1.728$, $b_{age} = -0.069$, $SE = 0.062$, $p = .265$, $b_{age\_squared} = -0.013$, $SE = 0.004$, $p = .001$). The model-predicted heart rates were 80.93, 84.11, and 78.20 beats per minute at ages 22 years (M_{age} – 1 SD), 41 years (M_{age}), and 60 years (M_{age} + 1 SD), respectively. Within-person means of reports of being wide-awake and of participants' heart rate (averaged across all measurement occasions) were therefore included as control variables in the analyses reported below.

Associations Between Psychological and Physiological Measures of Arousal

To investigate associations between psychological and physiological arousal, we specified multilevel regression models analyzing whether participants' self-reported tense arousal (feeling nervous) and energetic arousal (feeling wide-awake) predicted their momentary heart rate above and beyond their momentary physical activity, and controlling for their average heart rate.

Self-reported tense arousal and momentary heart rate. Results reveal an association between self-reports of feeling nervous and momentary elevations of participants' heart rates that were more pronounced the more nervous participants reported feeling (see Table 1 and Figure 1).

Model specification. We included participants' reports of how nervous they felt momentarily (tense arousal), their age (grand-mean centered), and the respective cross-level interaction as independent variables in our analyses. Participants' momentary physical activity and their average heart rate were grand-mean centered and served as control variables. The Age × Feeling Nervous interaction did not reach significance ($p > .05$) and was therefore not included in the interest of model parsimony. In other words, there was no evidence that the association between reports of feeling nervous and momentary heart rate differed depending on participants' age. There also were no significant quadratic age effects ($p > .05$). The quadratic effect of feeling nervous, however, was significant and hence included as an additional predictor of heart rate. We removed the random effects of feeling nervous from the final model because the parameter estimate was non-significant and a likelihood ratio test on the change in deviance indicated that removing this term did not impair the overall model fit; $\chi^2(\text{df} = 1) = 0, p = 1$.

Parameter estimates of the resulting model are shown in Table 1. The interpretation of the fixed effects is equivalent to those of unstandardized coefficients in ordinary least squares regression, that is, the intercept represents the average momentary heart rate when all predictors are zero (i.e., are at their mean values), and the slopes denote the differential in momentary heart rate for a one-unit increase in a given predictor variable when the other predictors are at their mean values (i.e., controlling for the effects of the other predictors). The model-predicted increase in heart rate between situations in which participants reported not feeling nervous at all and those in which they reported feeling very nervous was 11.69 beats per minute.

Self-reported energetic arousal and momentary heart rate. Our investigation of associations between energetic arousal and heart rate followed the same rationale, using reports of feeling wide-awake as the indicator of momentary energetic arousal. Results reveal a significant Age × Feeling Wide-Awake interaction (see Table 2). There was no indication of non-linear effects of age or of feeling wide-awake on momentary heart rate. These squared terms were therefore not included as model predictors. Furthermore, the parameter estimate of the random effect of feeling wide-awake was not significant and removing it from the model did not impair the overall model fit: $\chi^2(\text{df} = 1) = 0$, $p = 1$. Figure 2 illustrates the Age × Feeling Wide-Awake interaction by depicting the association between feeling wide-awake and predicted heart rate for the average age as well as for one standard deviation below and above the average age. Examination of the figure reveals an age-related decrease in the strength of the association between reports of feeling wide-awake and momentary heart rate. Region-of-significance analyses (Bauer & Curran, 2005; Preacher, Curran, & Bauer, 2006) showed that only for participants aged 49.64 years and younger was feeling more wide-awake associated with an increase in momentary heart rate. At the age of 22 years ($M_{\text{age}} - 1$ *SD*), for example, the model-predicted increase in heart rate between situations in which participants reported not feeling wide-awake at all and those in which they reported feeling very wide-awake was 5.96 beats per minute. The association between feeling wide-awake and momentary heart was not significantly different from zero for participants older than 49.64 years.

Arousal and Working-Memory Performance

We had hypothesized that the association of higher levels of arousal with lower working-memory performance increases with age. To investigate this prediction, we specified multilevel regression models analyzing whether age moderates the association between working-memory performance and psychological or physiological measures of momentary arousal. The dependent variable in these analyses was the participants' momentary working-memory performance.

Associations of Working-Memory Performance With Tense Arousal and Energetic Arousal. Results provided no evidence for possible age-related differences in the association between feeling wide-awake and working-memory performance. They confirmed, however, the hypothesized age-related increase in the strength of the association between reports of feeling nervous and lower momentary working-memory performance (see Table 3 and Figure 3).

Model specification. Participants' momentary endorsements of feeling nervous (tense arousal) and feeling wide-awake (energetic arousal) served as predictors on the situation level. We initially also included the squared and interaction terms of these variables to investigate potential non-linear and interaction effects. We further included age (grand-mean centered) as a model predictor on the person level, as well as the cross-level interactions between age and the linear and squared terms of feeling nervous and feeling wide-awake. To control for age-related differences in average reports of feeling wide-awake, we also included the respective within-person average as a control variable (grand-mean centered). The parameter estimates for the squared arousal terms and the interaction between nervous and wide-awake did not reach statistical significance (all $p > .05$) and were therefore not included in further analyses, in the interest of model parsimony. The interaction of feeling wide-awake with age also did not reach statistical significance and was therefore not included in the final model ($p > .05$). We also removed the random effects of nervous and wide-awake from the final model, because the parameter estimates were non-significant and likelihood ratio tests on the change in deviance indicated that removing these terms did not impair the overall model fit; wide-awake: $\chi^2(\text{df} = 1) = 0$, $p = 1$; nervous: $\chi^2(\text{df} = 1) = 2.3$, $p = .129$.

Parameter estimates of the resulting model are shown in Table 3. In line with our hypothesis, the interaction between age and feeling nervous reached statistical significance. Figure 3 illustrates the interaction by depicting the predicted values of the model in Table 3 for the average age as well as for one standard deviation below and above the average age. Region-of-significance analyses (Bauer & Curran, 2005; Preacher et al., 2006) showed that the negative association between feeling nervous and momentary working-memory performance was significant for participants aged 45.65 years and older, but not significantly different from zero for participants younger than that. Within the significant age range, the strength of the association increased further. At the age of 60 years (M_{age} + 1 *SD*), for example, the model-predicted decrease in working-memory performance between situations in which participants reported not feeling nervous at all and those in which they reported feeling very nervous was 15.55%.

Parameter estimates of the Age × Feeling Nervous interaction only changed very little numerically but failed to maintain significance, after we also controlled for momentary type of activity (–0.071, $SE = 0.038$, $p = .060$), social partner/s (–0.072, $SE = 0.037$, $p = .055$), and the linear and squared effects of time of day (–0.068, $SE = 0.0372$, $p = .066$). The parameter estimate was comparatively most attenuated when we additionally controlled for momentary heart rate (–0.062, *SE* = 0.0393, *p* = .114).

Association of Working-Memory Performance with Momentary Heart Rate. Corresponding to the pattern of findings reported earlier for tense arousal, analyses also revealed an age-related increase in the strength of the association between physiological activation and momentary working-memory performance (see Table 4 and Figure 4).

Model specification. We specified a model with momentary heart rate (linear and squared effects) and age, as well as the cross-level interactions between age and the linear and squared heart-rate terms as predictors of momentary working-memory performance. Momentary physical activity and within-person average heart rate were included as control variables. Momentary heart rate was person-mean centered. Parameter estimates thus indicate whether heart-rate fluctuations above and below a given participant's average heart rate are predictive of fluctuations in working-memory performance. We chose this centering method because it controls for individual differences in average heart rate (for example, due to differences in physical fitness or aging, Ferrari, Radaelli, & Centola, 2003). All other parameter estimates were grand-mean centered so that the focal Age × Heart Rate interaction could be interpreted under the assumption that the other predictors are at the sample mean (i.e., controlling for the effects of the other predictors). The parameter estimate for squared heart rate did not reach statistical significance, and neither did the respective interaction with age (all $p > .05$). In other words, there was no evidence of a non-linear association between heart rate and working-memory performance, and this was the case independent of participants' age. These effects were thus not included in further analyses. We also removed the random effects of heart rate and physical activity from the final model because their parameter estimates were not significantly different from zero (all $p > .05$), and because fixing these effects across participants did not significantly impair the overall model fit as indicated by likelihood ratio tests on the change in deviance; heart rate: χ^2(df = 1) = 0.3, *p* = .584, physical activity: χ^2(df = 1) = 0.5, *p* = .480.

Parameter estimates of the resulting model are shown in Table 4. In line with our hypothesis and mirroring the findings for tense arousal reported earlier, the interaction between age and heart rate reached statistical significance. Control analyses showed that parameter estimates of this interaction remained robust when we additionally controlled for participants' momentary type of activity (–0.009, *SE* = 0.005, *p* = .049), their momentary social partner/s (–0.010, *SE* = 0.005, *p* = .037), or their momentary reports of feeling nervous (–0.009, *SE* = 0.005, *p* = .046), and just failed to reach significance when we controlled for the linear and squared effects of time of day (–0.009, *SE* = 0.005, *p* = .051).

Figure 4 illustrates the interaction by depicting the predicted values of the model in Table 4 for the average age as well as for one standard deviation below and above the average age. Inspection of the figure reveals the hypothesized facilitative effect of low physiological arousal for older participants. Region-of-significance analyses (Bauer & Curran, 2005; Preacher et al., 2006) showed that the negative association between momentary heart rate and momentary working-memory performance was significant for participants aged 56.69 years and older, but not significantly different from zero for participants younger than that. Within the significant age range, the association strength increased further. At the age of 60 years (M_{age} + 1 *SD*), for example, the model-predicted decrease in working-memory performance between the minimum and the maximum of the observed range of heart-rate deviations from individual means was 15.27%. Region-of-significance analyses further showed that age differences in momentary working-memory performance reached statistical significance in situations in which participants' heart rate deviated by 15.09 or more beats per minute below their individual average heart rate.

To further follow up on the latter result, we divided the observed heart-rate distribution of each participant into three intervals, each including about equal numbers of observations: low, medium, and high momentary heart rate *for this individual*. Participants' heart rates in the low- and medium-arousal segments were comparable across the investigated age range as indicated by non-significant correlations between participants' age and their average heart rates in these segments ($r = -.01$, $p = .95$; and $r = -.15$, $p = .17$, respectively). A significant age correlation emerged only in the high-arousal segment. The older the participants were, the lower their average heart rate was in the high-arousal segment ($r = -.25$, $p = .02$).[3]

Correlations between participants' age and the average working-memory performance in each of these heart-rate segments revealed a small age-related performance advantage in the low-arousal segments. Working-memory performance in low-arousal segments was slightly better the older the participants were ($r = .25$, $p = .02$). No age-related performance differences emerged in the medium-arousal and high-arousal segments ($r = .10$, $p = .34$, and $r = –.04$, $p = .72$, respectively).

Situational contexts of low-arousal segments. The purpose of the set of analyses described here was to further explore the situational contexts of low-arousal segments. Results indicate that low-arousal segments were more likely to occur earlier during the day and when participants were momentarily less physically active. The dependent variable in these analyses was whether (or not) a given measurement occasion referred to a low-arousal segment. We used the macro provided by Van Ness, O'Leary, Byers, Fried, and Dubin (2004) to estimate multilevel binary logistic regression models in SAS NLMIXED.

Model specification. We first specified a model with age as predictor on the person level, and time of day, physical activity, tense arousal (feeling nervous) and energetic arousal (feeling wide-awake) as predictors on the situation level. Time of day was centered at 6 a.m.

(i.e., the approximate time of the earliest measurement taken in this study), and physical activity was centered at the grand mean. We initially also included the respective quadratic terms as well as all cross-level interactions with age in the model. With the exception of time of day, none of the quadratic terms reached statistical significance, and neither did the estimates for age, feeling nervous, feeling wide-awake, and any of the age interactions ($p >$ .05). In the interest of parsimony, we therefore excluded these effects from further analyses. Results showed that the likelihood of low-arousal segments was highest in the mornings and declined thereafter (odds ratio of time of day, centered at 6 a.m = 0.74, $p < .05$). This decline in the likelihood of low-arousal segments decelerated throughout the day (odds ratio of squared time of day = 1.01, $p < .05$). Low-arousal segments were also more likely to occur in situations with lower momentary physical activity (odds ratio of momentary physical type of activity, grand-mean centered = 0.44, $p < .05$). These effects were independent of participants' age ($p > .05$ for all interactions with age). Further analyses showed that the likelihood of low-arousal segments was unrelated to the participants' momentary type of everyday activity or social partner, irrespective of participants' age (all $p > .05$).

Discussion

The purpose of the present study was to contribute to a better understanding of short-term fluctuations in working-memory performance, and particularly to a better understanding of contextual influences that allow older adults to fully exploit their working-memory potential. With this aim, we investigated the co-variation between naturally occurring fluctuations in psychological and physiological measures of arousal and performance in a well-practiced working-memory task. We expected older adults to reach their performance maximum at lower levels of tense (but not energetic) arousal than younger individuals do. We investigated this prediction in participants ranging in age from adolescence to old adulthood, using mobile-phone based experience sampling and ambulatory ECG recordings.

Findings from this study provide further support for the distinctiveness of tense and energetic dimensions of psychological arousal (Schimmack & Reisenzein, 2002; Thayer, 1996). This was evident in three respects. First, we found differential age effects on energetic versus tense arousal: The older participants were the more they tended to endorse feelings of being wide-awake (energetic arousal). There was however no indication of age differences in participants' average tendency to report feeling nervous (tense arousal).

Second, we found differential patterns of associations with participants' momentary heart rate. An increase in self-reported tense arousal was associated with an accelerated increase in momentary heart rate, and this was so independent of participants' age. Energetic arousal was also associated with an increase in momentary heart rate, however only in participants who were younger than 50 years. There was no systematic association between feeling wide-awake and momentary heart rate in participants who were older than that. Together with the observed age-related increase in the prevalence of energetic arousal, this finding suggests the possibility of age-related changes in the experience and physiological correlates of energetic arousal. Another possibility is that older participants interpreted the meaning of the "wide-awake" item differently than younger individuals did. Future research is necessary to disentangle these possibilities empirically.

Third, we found differential patterns for the associations of tense arousal and energetic arousal with momentary working-performance. Energetic arousal was unrelated to within-person fluctuations in momentary working-memory performance, and this was true irrespective of participants' age. In agreement with our prediction, however, we found that experiences of tense arousal were associated with lower working-memory performance in a well-practiced task, but only in participants older than 45 years. This Age × Tense Arousal interaction, however, ceased to reach significance when we additionally controlled for participants' momentary heart rate. Taken together, this pattern of findings indicates that subjective arousal experiences are associated with lower working-memory performance in middle-aged and older adults, but only when they are accompanied by heightened physiological activation in these age groups. In fact, it is possible that the accompanying heightened physiological activation drives the associated decrease in working-memory performance.

This latter interpretation is nourished by the finding that a corresponding age moderation also emerged for the negative association between heart rate and working-memory performance, which reached statistical significance at the age of 56 years. This effect remained significant after controlling for momentary reports of feeling nervous, which indicates that also heightened physiological arousal that derives from other sources of activation than experiences of tense arousal (e.g., from physical activity or circadian rhythms, see below) is accompanied by impaired working-memory performance in middle-aged and older adults. Overall, this finding is consistent with the proposition of an age-related increase in vulnerabilities associated with physiological arousal (Charles, 2010). The present study demonstrates that these vulnerabilities can already become manifest in middle adulthood. Taken together, our findings emphasize that arousal levels need to be considered when investigating age differences in working-memory performance.

There was no evidence of non-linear associations between psychological and physiological arousal and working-memory performance, and this was the case independent of participants' age. Whereas middle-aged and older participants reached higher working-memory performance the lower their levels of tense arousal or physiological activation were, no optimal ranges of arousal for working-memory performance could be distinguished for younger participants. Possible reasons for this could be that the optimal arousal level for these individuals was not within the range of spontaneously occurring heart-rate fluctuations observed while participants pursued their normal daily routine, or that the task was less challenging for younger individuals than for older participants.

In physiologically relaxed states, the participants even performed slightly better on the well-practiced working-memory task the older they were. This finding was unexpected given the vast number of laboratory studies showing an age-related decrease in working memory throughout adulthood. Selectivity analyses did not support the possibility that this finding may have been due to the older subsample not being representative in terms of its cognitive capacity. Instead, there were two characteristics of our research that we consider particularly important.

First, assessments were obtained in real-life contexts and while participants pursued their normal routines. Participants had to sustain task motivation throughout 24 hours and without the help of external motivators. In laboratory studies, in contrast, external control of task motivation is provided, for example, by the specific test setting that participants attend for a confined time period, and by the presence of an experimenter and/or fellow participants, which might heighten the salience of the evaluative component of task performance. An interesting question for future research therefore is to what extent possible age differences in self-regulated (intrinsic) task motivation may have contributed to the present pattern of findings. For example, it is possible that younger participants were less motivated than older adults to perform well in the task because no obvious external control instance was available. They may thus have invested themselves less in the task than they would have in controlled laboratory contexts. Another pattern of age differences could hence evolve in situations in which external control minimizes the relevance of self-regulated (i.e., intrinsic) task motivation.

Second, the working-memory task had been practiced intensively prior to this study. Methodologically, this disambiguated the interpretation of the observed age differences in the link between arousal and working memory because it eliminated age differences in average task performance. Even though participants still had to maintain and manipulate several pieces of information in their working memory to do the task, the practice-related gain in efficiency of doing so may have shifted the characteristics of the task from occupying much of the available working-memory capacity to primarily requiring persistent allocation of attention and concentration. Future research should therefore investigate age differences in associations between arousal and performance levels when participants operate at the limits of their working-memory capacity, and try to disentangle the age-differential role of arousal for various aspects of working-memory performance.

Situations with low physiological activation were more likely to occur earlier in the day and, not surprisingly, when participants were less physically active in the moments immediately preceding the assessment of the working-memory tasks. This study thus adds to prior research that showed a shift throughout adulthood in the timing of subjective performance peaks to increasingly earlier times of day. This prior research also demonstrated that not being tested at their subjective peak time disproportionately disadvantages older adults' working-memory performance, more so than it does younger individuals' (e.g., Hasher, Chung, May, & Foong, 2002; Rowe, Hasher, & Turcotte, 2009; West, Murphy, Armilio, Craik, & Stuss, 2002). The present study suggests that age differences in the range of physiological activation that optimally facilitates working-memory performance may be among the mechanisms that underlie these observations. It thus adds further support to the warning that the cognitive potential of older adults could be underestimated when assessments are scheduled at non-optimal (i.e., later) times of the day (e.g., Hasher et al., 2002; Rowe et al., 2009). Our findings also highlight a further potential problem. The cognitive potential of older adults may also be likely to be underestimated when the study setting evokes experiences of tense arousal or has an otherwise activating effect on the participants' physiological arousal level. The novelty or the evaluative character of the testing situation, for example, can elicit feelings of tense arousal. Age-related stereotype threat, that is, concern that one will confirm a negative stereotype about one's age group (Schmader, Johns, & Forbes, 2008), also enhances tense arousal, and may be evoked when older participants are asked to perform cognitive tasks. The cognitive potential of older adults may also be underestimated in situations in which participants are physically active before or during the assessment.

Limitations and Outlook

Important questions that the present study cannot address pertain to the mechanisms that underlie the observed negative association of experiences of tense arousal and physiological activation on working-memory performance in middle-aged and older adults, and to the reasons why no such age moderation was observed for energetic arousal. We had derived our respective predictions from the idea that increasing arousal narrows the range of information items that individuals attend to at a given point in time (Easterbrook, 1959). We had reasoned that the optimal range of arousal for a certain task thus depends not only on the number of information items that need to be processed, but also on the attentional capacity of the individual. An interesting task for future research would be to directly investigate implications of energetic and tense arousal and physiological activation for the processing of information, and potential age-related differences therein. In addition to the respective role of the range of information attended to, future research should also consider arousal influences on other aspects of information processing relevant in working memory, such as the intrusion of irrelevant thoughts, the deletion of no longer relevant information, or the inhibition of pre-potent responses (Hasher, Zacks, & May, 1999). Another potentially mediating process could derive from age differences in the motivation to down-regulate unpleasant experiences associated with tense arousal. Previous research suggests an age-related increase in individuals' motivation to maximize their momentary emotional well-being (e.g., Carstensen, Fung, & Charles, 2003; Riediger, Schmiedek, Wagner, & Lindenberger, 2009). There may thus be an increase with age in the motivation to down-regulate tense arousal. This may not be the case for energetic arousal, as it is likely the subjectively more pleasant state. To the extent that affect-regulatory efforts require investment of cognitive resources (e.g., Gross, 2008), this may thus lead to an age-related increase in the depletion of cognitive capacity in tense-arousal situations.

A notable limitation of the present study is that experiences of energetic and tense arousal were assessed with only one item each. Their measurement quality was sufficient for the present study, as indicated by reliable covariation with participants' heart rate and working-memory performance in various age groups. Nevertheless, use of more comprehensive measures in the future would be desirable to optimize the psychometric properties of the assessment. Another obvious limitation of the present research is the cross-sectional nature of the observed age-related differences. Longitudinal evidence is necessary in the future to address the question whether and to what extent the observed age-related differences arise from differences between birth cohorts and/or from aging-related within-person changes when people get older.

Summary and Conclusion

The present study employed ambulatory assessment to investigate age-related differences in the association between naturally occurring fluctuations in psychological and physiological arousal and performance in a well-practiced working-memory task, measured in participants' daily life contexts. Participants varied in age between 14 and 83 years. Their performance in a standard perceptual-speed task was comparable to that of their age peers in a large-scale representative household panel. Participants had extensively practiced the working-memory task prior to participating in the present study, which eliminated age-related mean differences in working-memory performance and thus disambiguated the interpretation of the observed results, but may also have modified the demand characteristics compared to the unpracticed task. Experiences of tense arousal as well as increases in heart rate were associated with lower working-memory performance in middle-aged and older participants. An interesting finding was that participants in physiologically relaxed states performed slightly better on the well-practiced working memory task the older they were. Overall, the present research suggests that studies may overestimate adult age differences in cognitive performance when they do not consider the role of tense arousal and physiological activation. This seems likely when the assessment situation itself elicits feelings of tense arousal (e.g., due to its novelty, or its evaluative and/or stereotype-threat evoking character), when participants have to be physically active before or during the assessment, or when assessments are scheduled in the afternoon or evening.

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Footnotes

[1] The present study is part of a larger research project. Prior to the data collection reported here, another part of the project had taken place in which participants gained extensive practice in the working-memory task. The present study took place, on average, 8.4 months, *SD* = 0.9, after this initial practice phase.

[2] Average Symbol-Digit performance in SOEP sample: *M* = 31.20, *SD* = 9.94 (< 18 years); *M* = 33.23, *SD* = 9.99 (18–29 years); *M* = 30.58, *SD* = 9.51 (30–39 years); *M* = 28.18, *SD* = 8.89 (40–49 years); *M* = 26.03, *SD* = 8.56 (50–59 years); *M* = 23.10, *SD* = 8.59 (60–70 years); *M* = 19.99, *SD* = 8.39 (70+ years). Average Symbol-Digit performance in present sample: *M* = 33.40, *SD* = 8.09 (< 18 years); *M* = 35.22, *SD* = 9.40 (18–29 years); *M* = 28.67, *SD* = 8.42 (30–39 years); *M* = 31.42, *SD* = 7.01 (40–49 years); *M* = 23.36, *SD* = 6.56 (50–59 years); *M* = 26.73, *SD* = 6.08 (60–70 years); *M* = 23.33, *SD* = 7.66 (70+ years).

[3] Descriptive information on the heart-rate distributions in the low, medium and high arousal segments (in beeps per minute): (a) < 18 years: *M* = 75.7, *SD* = 11.5; *M* = 84.2, *SD* = 11.4; *M* = 91.6, *SD* = 9.0, respectively. (b) 18 to < 35 years: *M* = 68.0, *SD* = 8.0; *M* = 76.4, *SD* = 8.9; *M* = 89.0, *SD* = 10.3, respectively. (c) 35 to < 59 years: *M* = 78.6, *SD* = 11.5; *M* = 86.4, *SD* = 11.8; *M* = 94.5, *SD* = 10.9, respectively. (d) > 59 years: *M* = 67.7, *SD* = 7.9; *M* = 72.5, *SD* = 9.9; *M* = 80.3, *SD* = 11.4, respectively.

Table 1.

Associations Between Feeling Nervous (Self-Reported Tense Arousal) and Momentary Heart Rate: Results from Multilevel Regression

	Predicting momentary heart rate		
Model parameters	Estimate	SE	*p*
Fixed effects			
Intercept	79.938	0.369	**
Age [a]	0.051	0.018	**
Feeling nervous [b]	-1.076	0.767	n.s.
Feeling nervous squared [b]	0.504	0.218	*
Momentary physical activity [a, c]	4.048	0.408	**
Individual average heart rate [a]	0.975	0.029	**
Random effects			
Intercept [d]	-	-	-
Momentary physical activity [a, c]	3.932	1.647	**
SP(POW) [e]	0.963	0.020	**
Residual [f]	49.013	3.037	**
Modeled variance			
Within persons (Pseudo R^2_{Residual}) [g]	41.896%		

Notes. Restricted maximum likelihood parameter estimates in multilevel regression models with spatial power residual covariance structures (Littell et al., 2007).

[a] Grand-mean centered (deviations from sample mean). [b] Scale range: 0 –6. [c] Log-transformed. [d] Intercept variance (between-person variance in momentary heart) was completely accounted for by inclusion of the individuals' average heart rate as control

variable. [e] Autoregressive parameter (estimated covariance of two adjacent measurements assuming they were taken one hour apart). [f] Residual (remaining within-person) variance. [g] Proportional reduction in the residual variance component in comparison to models without explanatory variables (Singer & Willet, 2003).

n.s. $p > .05$. * $p < .05$. ** $p < .01$.

Table 2.

Associations Between Feeling Wide-Awake (Self-Reported Energetic Arousal) and Momentary Heart Rate: Results from Multilevel Regression

Model parameters	Predicting Momentary Heart Rate		
	Estimate	SE	*p*
Fixed effects			
Intercept	78.206	0.744	**
Age[a]	0.112	0.039	**
Feeling wide-awake	0.582	0.200	**
Age × Feeling wide-awake	-0.022	0.011	*
Momentary physical activity [a, b]	3.963	0.403	**
Individual average heart rate [a]	0.973	0.029	**
Random effects			
Intercept [c]	-	-	-
Momentary physical activity [a, b]	3.715	1.639	*
SP(POW) [d]	0.961	0.023	**
Residual [e]	48.739	3.024	**
Modeled variance			
Within persons (Pseudo $R^2_{Residual}$) [f]	42.221%		

Notes. Restricted maximum likelihood parameter estimates in multilevel regression models with spatial power residual covariance structures (Littell et al., 2007).

[a] Grand-mean centered (deviations from sample mean). [b] Log-transformed. [c] Intercept variance (between-person variance in momentary heart) was completely accounted for by inclusion of the individuals' average heart rate as control variable. [d] Autoregressive

parameter (estimated covariance of two adjacent measurements assuming they were taken one hour apart). [e] Residual (remaining within-person) variance. [f] Proportional reduction in the residual variance component in comparison to models without explanatory variables (Singer & Willet, 2003).

n.s. $p > .05$. * $p < .05$. ** $p < .01$.

Table 3.

Age and Tense Arousal (Feeling Nervous) Interact in the Prediction of Momentary Working-Memory Performance: Results from Multilevel Regression

	Predicting working-memory performance		
Model parameters	Estimate	SE	*p*
Fixed effects			
Intercept	84.255	2.048	**
Age [a]	0.113	0.070	n.s.
Feeling wide-awake [b]	0.669	0.494	n.s.
Feeling nervous [b]	-1.193	0.686	n.s.
Age × Feeling nervous	-0.074	0.038	*
Individual average of wide-awake [a]	-1.593	1.429	n.s.
Random effects			
Intercept [c]	80.065	18.620	**
SP(POW) [d]	0.980	0.005	**
Residual [e]	219.39	14.907	**
Modeled variance			
Between persons (Pseudo $R^2_{\text{Intercept}}$) [f]	4.82%		

Notes. Restricted maximum likelihood parameter estimates in multilevel regression models with spatial power residual covariance structures (Littell et al., 2007).

[a] Grand-mean centered (deviations from sample mean). [b] Scale range: 0 –6. [c] Conditional intercept variance (remaining between-person variance in working-memory performance). [d] Autoregressive parameter (estimated covariance of two adjacent measurements assuming they were taken one hour apart). [e] Residual (remaining within-person) variance. [f] Proportional

reduction in the intercept variance component in comparison to models without explanatory variables (Singer & Willet, 2003).

n.s. $p > .05$. * $p < .05$. ** $p < .01$.

Table 4.

Age and Momentary Heart Rate Interact in the Prediction of Momentary Working-Memory Performance: Results from Multilevel Regression

	Predicting working-memory performance		
Model parameters	Estimate	SE	*p*
Fixed effects			
Intercept	85.794	1.144	**
Age [a]	0.045	0.065	n.s.
Momentary heart rate [b]	-0.113	0.092	n.s.
Age [a] × Momentary heart rate [b]	-0.009	0.005	*
Momentary physical activity [a, c]	-0.194	0.845	n.s.
Individual average heart rate [a]	-0.218	0.106	*
Random effects			
Intercept [d]	74.081	18.134	**
SP(POW) [e]	0.980	0.005	**
Residual [f]	221.38	15.390	**
Modeled variance			
Between persons (Pseudo $R^2_{Intercept}$) [f]	11.93%		

Notes. Restricted maximum likelihood parameter estimates in multilevel regression models with spatial power residual covariance structures (Littell et al., 2007).

[a] Grand-mean centered (deviations from sample mean). [b] Person-mean centered (deviations from individual's mean). [c] Log-transformed. [d] Conditional intercept variance (remaining between-person variance in working-memory performance). [e] Autoregressive parameter (estimated covariance of two adjacent measurements assuming they were taken one hour

apart). [f] Residual (remaining within-person) variance. [g] Proportional reduction in the intercept variance component in comparison to models without explanatory variables (Singer & Willet, 2003).

n.s. $p > .05$. * $p < .05$. ** $p < .01$.

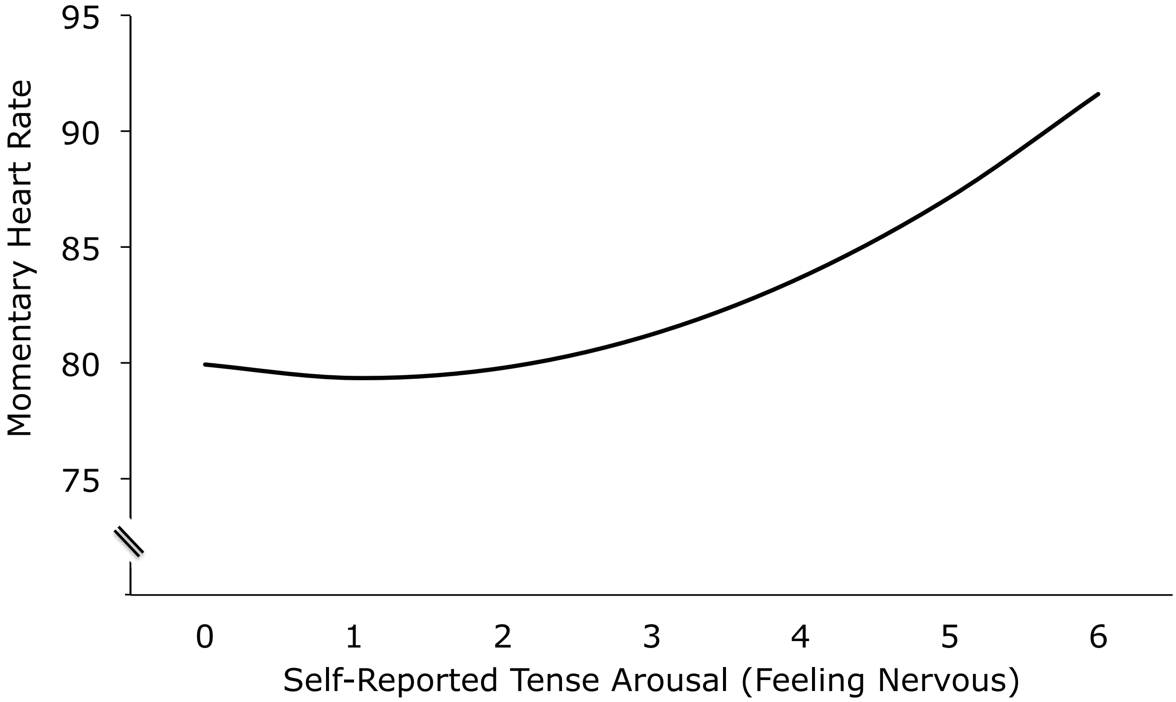

Figure 1. Model-predicted associations between self-reported tense arousal (feeling nervous) and momentary heart rate, controlling for momentary physical activity and individual average heart rate.

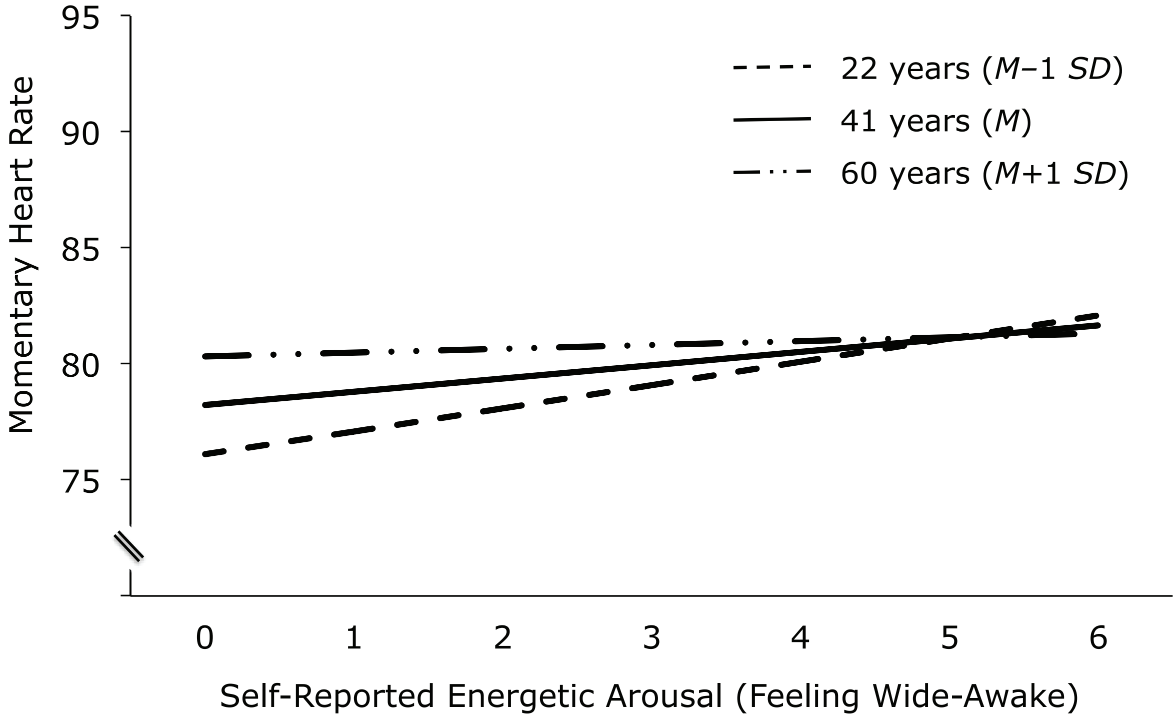

Figure 2. Model-predicted associations between self-reported energetic arousal (feeling wide-awake) and momentary heart rate for participants aged one standard deviation below, at, and one standard deviation above the sample mean, controlling for momentary physical activity and individual average heart rate.

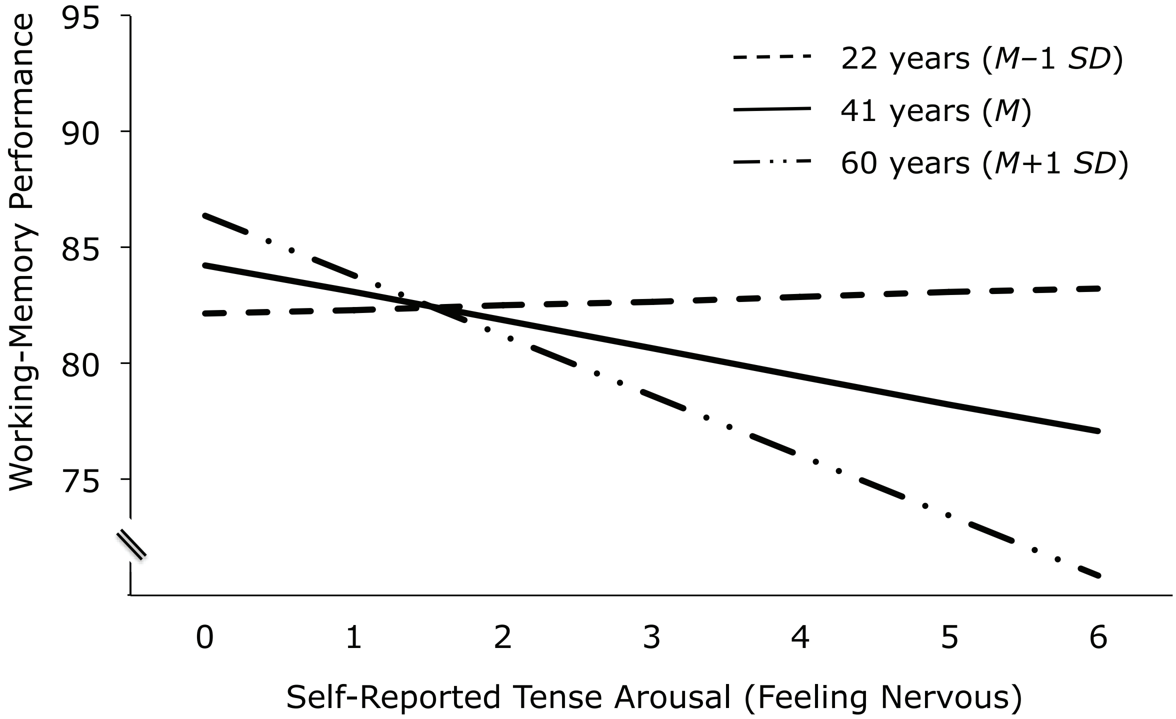

Figure 3. Model-predicted associations between self-reported tense arousal (feeling nervous) and momentary working-memory performance for participants aged one standard deviation below, at, and one standard deviation above the sample mean. Note. *M* = mean, *SD* = standard deviation.

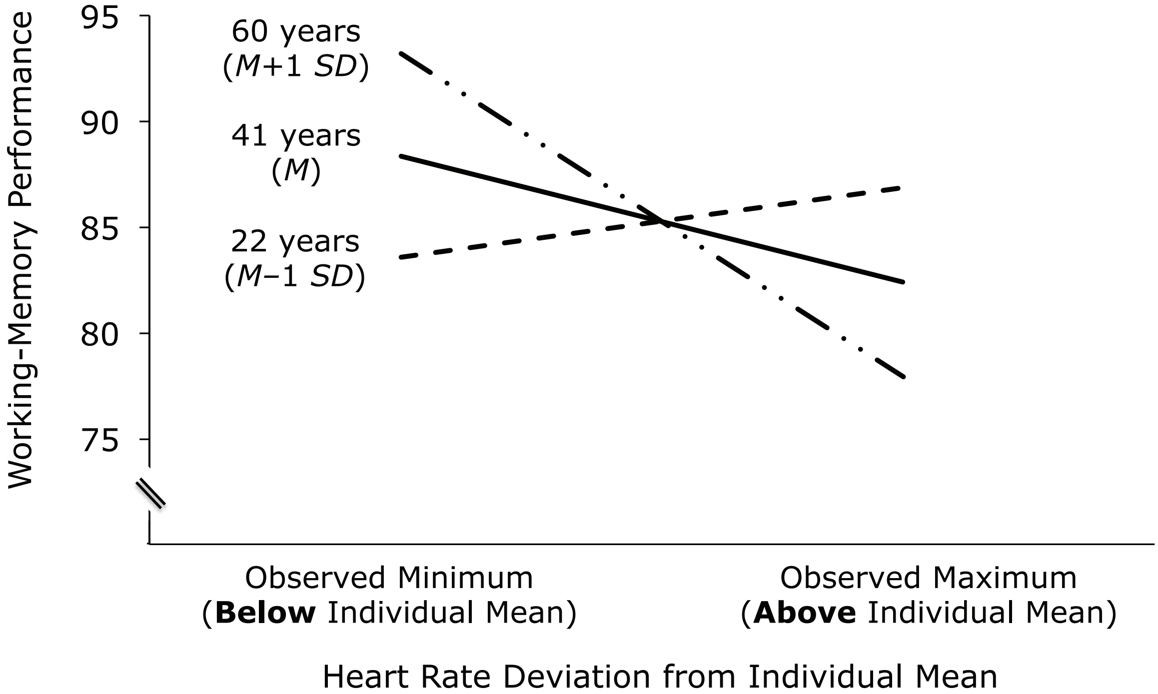

Figure 4. Model-predicted associations between momentary heart rate deviations from the individuals' respective means and their momentary working-memory performance for participants aged one standard deviation below, at, and one standard deviation above the sample mean. Note. *M* = mean, *SD* = standard deviation.