Induced Negative Arousal Modulates the Speed of Visual Working Memory Consolidation

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Abstract

This study examines how induced negative arousal influences the consolidation of fragile sensory inputs into durable working memory (WM) representations. Participants performed a visual WM change detection task with different amounts of encoding time manipulated by random pattern masks inserted at different levels of memory-and-mask Stimulus-Onset-Asynchrony (SOA). Prior to the WM task, negative or neutral emotion was induced using audio clips from the International Affective Digital Sounds (IADS). Pupillometry was simultaneously recorded to provide an objective measure of induced arousal. Self-report measures of early-life stress (i.e., adverse childhood experiences) and current mood states (i.e., depressed mood and anxious feeling) were also collected as covariates. We find that participants initially remember a comparable number of WM items under a short memory-and-mask SOA of 100 ms across emotional conditions, but then encode more items into WM at a longer memory-and-mask SOA of 333 ms under induced negative arousal. These findings suggest that induced negative arousal speeds up WM consolidation. Yet, induced negative arousal does not seem to significantly affect participants' WM storage capacity estimated from a separate no mask condition. Furthermore, this emotional effect on WM consolidation speed is moderated by key affect-related individual differences. Participants who have greater pupil responses to negative IADS sounds or have more early-life stress show faster WM consolidation under induced negative arousal. Collectively, our findings reveal a critical role of phasic adrenergic responses in the rapid consolidation of visual WM content and identify potential moderators of this association.

Keyword: Emotion, Negative Arousal, Working Memory, Consolidation, Capacity.

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Information encoded under negative arousing emotion is often remembered with greater details (Kensinger, 2009), higher fidelity (Xie & Zhang, 2017c), and elevated subjective feelings of remembering in long-term memory (Rimmele et al., 2011, 2012; Xie & Zhang, 2017c). These emotional memory effects have been found to rely upon the adrenergic system under the influence of arousal (i.e., the intensity of an emotional experience, Mather, Clewett, Sakaki, & Harley, 2016; Sara, 2009), especially when an emotional experience is negative in valence (e.g., Kensinger, 2007; Kensinger et al., 2007; Xie & Zhang, 2017c, but see Talarico, LaBar, & Rubin, 2004). Parallel to these well-documented findings in long-term memory, a rapidly growing body of research demonstrates similar effects of negative arousal on information retention over a shorter period of time in working memory (WM, e.g., Mather et al., 2006; Spachtholz, Kuhbandner, & Pekrun, 2014; Xie & Zhang, 2016a). For example, induced negative arousal may boost the precision aspect of retained WM content (Long et al., 2020; Spachtholz et al., 2014; Xie & Zhang, 2016a) and disrupt control-related WM processes (Choi et al., 2013; Schoofs et al., 2008; Shackman et al., 2006) or the ability to simultaneously retain multiple WM items (Long et al., 2020; Spachtholz et al., 2014). These observations are in line with the theoretical prediction that negative emotion can lead to more efficient use of cognitive resources but at the same time disrupt cognitive control (e.g., Eysenck et al., 2007). However, much of the evidence for these immediate effects of negative arousal on WM is mixed (Schweizer et al., 2019; Souza et al., 2020). Considering that WM retains a small amount of information to support a wide array of mental functions (Baddeley, 2012a; Cowan, 2001), the uncertainty about how emotion influences WM poses a great challenge to the understanding of the relationships between emotion and cognition across various areas of experimental psychology (Baddeley, 2012b).

One possibility is that emotion does not impact WM at all, as the WM system should operate robustly under any emotional contexts, especially when an emotional context is irrelevant to the to-be-remembered WM task contents (Souza et al., 2020; but see Baddeley, 2012a). However, this assertion appears to be at odds with the rich empirical observations that emotion often influences observers' WM task performance (e.g., Choi et al., 2013; Long et al., 2020; Schoofs et al., 2008; Shackman et al., 2006; Souza et al., 2020; Spachtholz et al., 2014; Xie & Zhang, 2016a; Y. Zhang, Zhang, & Liu, 2017). These inconsistent findings in the literature could reflect critical and substantive issues about additional factors that are not typically assessed but still influence behaviors significantly (Rosenthal & Rosnow, 2008). Delineating the conditions when a stronger emotional effect on WM may emerge can further promote the broader research efforts on the relationship between emotion and cognition, as well as their malfunctioning in psychiatric conditions (see a discussion in Eich, 1995). The primary goal of the current paper is, therefore, to move beyond the binary view on whether or not emotion influences WM by articulating the conditions under which emotion influences WM.

Time-dependent Influence of Induced Negative Arousal on WM Formation

Although previous research has examined the effects of induced negative arousal on WM representations or control-related processes (e.g., Choi et al., 2013; Shackman et al., 2006; Spachtholz et al., 2014), how induced negative arousal modulates the initial process of converting fragile sensory inputs into durable WM representations, namely the process of WM consolidation (Jolicoeur & Dell'acqua, 1998), has received surprisingly little attention in the literature. WM consolidation is a time-dependent process that is theoretically and empirically dissociable from WM maintenance and rehearsal (Bayliss et al., 2015; Woodman & Vogel, 2005). Furthermore, parallel to a limited WM storage capacity (Cowan, 2001; Luck & Vogel,

2013), the speed of WM consolidation can add another constraint on WM task performance (Alvarez & Cavanagh, 2004; Baddeley et al., 1975; Bundesen, 1990; Cavanagh, 1972; Jannati et al., 2015; Ricker et al., 2018; Vogel et al., 2006; Xie & Zhang, 2017b, 2018a). This time-dependent factor also plays an important role in modulating effect sizes in WM experiments, such as the effects of stimulus familiarity on WM task performance (Blalock, 2015; Ngiam et al., 2019; Xie & Zhang, 2017b, 2018a). If an experimental manipulation influences WM consolidation speed, its effects on WM task performance may primarily manifest during a certain stage of WM retention. Consequently, probing observers' WM task performance too early or too late may only yield a modest experimental effect (Xie & Zhang, 2017b). This possibility is partly supported by a recent study (Long et al., 2020), in which induced negative arousal results in greater effects on WM task performance when the study items are presented for 500 ms as compared with when they are presented for 200 ms. However, the manipulation of presentation duration influences both perceptual and WM processes. It remains unknown whether induced negative arousal influences WM consolidation when perceptual factors are held constant.

Two lines of previous studies have implicated the contributions of the arousal-related adrenergic system to WM consolidation. First, norepinephrine – as a key neurotransmitter mediating arousal responses – can improve the neurochemical mechanisms underlying sustained neural activities during WM retention (Arnsten, 2006, 2009; Wang et al., 2007), the neural hallmark of WM (Fuster & Alexander, 1971). Hence, pharmaceutical manipulations of adrenergic receptors in animal models can significantly change delay period neuronal activity and WM task performance (Arnsten, 2006; Ramos et al., 2008; Sawaguchi, 1998). Second, induced negative arousal can trigger the responses of locus coeruleus (LC) neurons, producing a widespread release of norepinephrine (Aston-jones & Cohen, 2005; Sara, 2009; Schwarzd &

Luo, 2015). While the tonic LC response is closely related to baseline pupil size, the phasic LC response is temporally specific to an triggering event, which can be captured by the transient change of pupil size time-locked to the event (Beatty, 1982a, 1982b; Beatty & Lucero-Wagoner, 2000; Gilzenrat et al., 2010). At a medium level, this event-locked LC phasic response prioritizes and facilitates the processing of task-relevant information via increases in sensory gain or reduction in neural noise, potentially as a result of boosted attention (Becker, 2009; Chajut & Algom, 2003; Mather et al., 2016; Todd et al., 2012; Vazey et al., 2018). These attention prioritization effects may subsequently lead to faster WM consolidation, considering that the consolidation of transient sensory inputs into durable WM representations requires the selection of task-relevant information into the focus of attention (see Raffone, Srinivasan, & van Leeuwen, 2014 for a discussion). The faster the focus of attention can be shifted to task-relevant contents, the faster one can encode these contents into WM, manifesting as a faster information cumulation slope over time (Figure 1A and 1D). However, given that WM storage capacity is associated with attention scope (Cowan, 2001) more so than with attention prioritization, induced negative arousal may therefore speed up WM consolidation without affecting the total amount of information one can remember in WM, which asymptotes at its storage capacity (Figure 1A).

However, it is also possible that induced negative arousal and its effect on attention may simply influence the likelihood of an item being encoded/consolidated into WM at a given time point, without altering the speed of consolidation. This hypothesis is in line with a close relationship between attention fluctuation and the number of retained WM items on a trial-by-trial basis (e.g., deBettencourt, Keene, Awh, & Vogel, 2019). As such, a transient change in attentional function, such as the scope of attention, may potentially impact the number of encoded WM items at a given moment (e.g., Sun, Zimmer, & Fu, 2011). This can reflect as an

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overall increase in task performance under induced negative arousal up to a boosted or a fixed storage capacity limit (Figure 1B and 1C, respectively). Alternatively, induced negative arousal can increase both WM consolidation speed and storage capacity (Figure 1D). These predicted effects of medium-level arousal on WM formation, however, do not preclude the potential decrement of overall task performance under high arousal (Yerkes & Dodson, 1908). Neither do these effects preclude the possibility that induced negative arousal can compromise the control-related processes potentially involved for simultaneously retaining several items (Eysenck et al., 2007), especially towards the later stages of WM retention (e.g., Long et al., 2020; also see Discussion). To test these possibilities, it is imperative to estimate both WM consolidation speed and storage capacity under the influence of induced negative arousal.

This study thus adopts a modified visual WM change detection task under induced negative arousal using audio clips from the International Affective Digital Sounds (IADS) system with negative (higher arousal) or neutral (lower arousal) valence (Bradley & Lang, 2007). The 6-second IADS audio clips with different arousal levels were played 5 seconds preceding the WM task and 1 second into the WM task with simultaneous pupillometry recording (Figure 2). Given the potentially nonlinear relationship between arousal and task performance (Yerkes & Dodson, 1908), we choose negative sounds with medium-level arousal based on normative ratings of IADS stimuli. We use the pupillary responses during the IADS presentation as an operational measure of the magnitude of induced arousal for each participant (e.g., Partala & Surakka, 2003). These pupillary responses are captured prior to the onset of the to-be-remembered items in the WM task, making it possible to separate phasic LC-norepinephrine pupillary response evoked by emotional sounds from pupillary responses evoked by the visual WM task (e.g., light reflex) or related to the anticipation of a cognitive task (Alnaes et al., 2014).

Furthermore, this phasic pupillary response also provides a physiological measure of individual differences in induced emotional experience that is more objective than subjective reports.

In the WM task, random pattern masks were inserted into the retention interval at different levels of Stimulus Onset Asynchrony (SOA) following a brief and fixed-duration presentation of the study items (Vogel et al., 2006). This fixed study duration holds perceptual factors constant across experimental conditions. In principle, only information already encoded into WM can survive the pattern masks, as these masks can interrupt post-sensory processing, if they could not completely terminate WM consolidation (Nieuwenstein & Wyble, 2014; Ricker & Hardman, 2017; Ricker & Sandry, 2018). Hence, more items can be retained in WM as memory-and-mask SOA increases until a storage capacity limit is reached (Vogel et al., 2006). Based on previous empirical observations using this paradigm, at a shorter SOA around 100 ms, participants can encode about 1 item into WM, whereas they can remember 2 to 3 items at a longer SOA around 300 ms (Ngiam et al., 2019; Vogel et al., 2006; Xie & Zhang, 2017a). These SOA time points therefore reflect the earlier and later consolidation phases, respectively. The difference in the numbers of encoded items between these SOA time points can therefore be used as a proxy measure for WM consolidation speed (Jannati et al., 2015; Xie & Zhang, 2017b). In theory, this measure captures certain time-dependent difference in the overall WM task performance that would require the involvement of WM consolidation to manifest given a fixed sensory encoding duration and retention interval (see some discussions and cautious notes in Ricker & Cowan, 2014). Experimental findings based on this measure of WM consolidation speed can be replicated using measures from more SOA time points (Ngiam et al., 2019) and event-related potential (ERP) measures of WM retention (Xie & Zhang, 2018a). Furthermore, this measure of WM consolidation can also be dissociable from a capacity estimate based on

change detection task performance when WM consolidation is not interrupted by the mask (Xie & Zhang, 2017b, 2018a). This study, therefore, included all three WM conditions, namely short- and long-SOA masking conditions as well as a no-mask condition, to allow within-subject assessment of both WM consolidation speed and storage capacity under different levels of induced arousal.

A Consideration of Individual Differences

The overall cognitive effects of emotion, including the potential impact of negative arousal on WM consolidation, may be modulated or even masked by some critical individual differences, such as observers' sensitivity to arousal induction (Bloise & Johnson, 2007; Elzinga & Roelofs, 2005; Larsen & Diener, 1987) and their past experiences in responses to stress (Chen & Baram, 2016; McLaughlin et al., 2014). However, these key moderators are often neglected or considered as background noise in previous studies of induced negative arousal and WM, adding to the uncertainty concerning how emotion influences WM (Souza et al., 2020). These moderators are testable using meta-analysis of existing data (Rosenthal & DiMatteo, 2001). However, this treatment is *post hoc* in nature and complicated by the availability of sufficient data and selection bias (see Rosenthal & DiMatteo, 2001; Xie, Cappiello, Meng, Rosenthal, & Zhang, 2018 for some discussions). Another approach is to explicitly test how these outstanding moderators may account for the variance in experimental observations (Rosenthal & Rosnow, 2008). In either case, delineating the effects of these moderators on the relationship between emotion and WM can clarify whether WM is immune to emotional influences or is a key component in an observer's response to emotion (Baddeley, 2012b). Hence, in the current study, we included two key theoretical moderators to explore how individual differences affect our experimental observations.

We first consider the effectiveness of arousal induction as a moderator. Some previous studies have used subjective reports as a proxy measure of this moderator (Long et al., 2020; Souza et al., 2020; Xie & Zhang, 2016a). However, these subjective reports sometimes do not correspond with induced emotional experiences captured by more objective physiological responses (Lang, 1970; Miers et al., 2011). Consequently, the reliance on subjective reports can yield mixed experimental findings in the literature (Souza et al., 2020). To resolve this issue, a more objective measure for the effectiveness of arousal induction is required, for example, the extent to which an observer's pupil dilates under negative relative to neutral IADS stimuli (e.g., Partala & Surakka, 2003). This measure partly reflects participants' sensitivity to the emotional sounds. The more sensitive they are to the negative sounds, the greater their pupils would dilate under negative relative to neutral sounds, indicating more effective arousal induction. We adopt this measure to assess the effectiveness of arousal induction and expect that the experiment outcomes of induced negative arousal should be more pronounced under effective arousal induction.

Next, we also investigate how participants' WM task performance is influenced by an apparent subject-level variable in our sample, which is early-life stress captured by adverse childhood experiences (ACEs, Anda et al., 2006; McLaughlin, Sheridan, & Lambert, 2014). We focus on this variable for the following reasons. First, in a previous survey study of 188 participants (94 female, 19.27 ± 1.13 years old) aiming to characterize our subject pool in the Inland Empire of California, we found that our participants reported significantly more ACEs, as compared with a norm established by 17,337 participants in the nearby San Diego county (observed: 18% vs. expected from the norm: 12.5%, $\chi^2_{(1)} = 5.70$, $p = .016$). This observation is consistent with socioeconomic data from U.S. Census Bureau of these regions (see

<https://www.census.gov/>) and is replicated in the fully separate sample of the current study (see Results). Second, ACEs can predict depressed mood and anxious feelings in adolescents and young adults in both cross-sectional and longitudinal studies (Anda et al., 2006; Lee et al., 2020; Michl et al., 2013). However, it is not yet understood how the enduring impacts of early-life stress (Anda et al., 2006) influence the interaction between emotion and WM. To explore this issue, we therefore examine the effect of ACEs on WM task performance under induced negative arousal.

Here, we would like to clarify that although we have included the consideration of these factors *a priori*, these moderator analyses are exploratory in nature. Yet, this does not undermine the importance of identifying the factors that may significantly influence our behaviors but are often neglected (Rosenthal & Rosnow, 2008). Identifying these factors would refine our understanding of the current findings, bringing the awareness of individual differences in the experimental research on human cognition (Vogel & Awh, 2008).

Study Preview

To examine the experimental effect of induced negative arousal on WM consolidation process and to explore individual differences that influence these experimental effects, we recruited 120 participants in the current study. First, we aimed to test the primary prediction that induced negative arousal at the medium level speeds up WM consolidation. We obtained significant evidence with a modest effect size supporting this prediction. Second, we examined the secondary prediction that individual differences, such as the effectiveness of arousal induction and participants' early-life stress, moderate the size of effect regarding the impact of induced arousal on WM consolidation. We observed significant evidence for these moderation effects, even after taking into consideration other additional covariates, such as participants'

mood states and gender. Overall, our data reveal a novel emotional impact on WM and point out key moderators in the interaction between emotion and WM.

Method

Participants

A total of 120 undergraduate students (80 female, 19.34 ± 2.09 [Mean $\pm$ SD] years old) were recruited for the current study in a single experimental session (~2 hours in total, with ~1 hour for the behavioral task) at the University of California, Riverside for course credits or monetary compensation (\$10/hour). The sample size of this study ($n = 120$) is larger than the sample size required to reveal a significant experimental effect ($\alpha = .05$) in a two-way repeated-measure analysis of variance (ANOVA) with 80% statistical power using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) based on a small-to-medium effect size (Cohen, 1992; e.g., Cohen's $f^2 = 0.02$ to 0.15 , required $n = 99$ to 14 , respectively). All participants reported normal (or corrected-to-normal) visual acuity and normal color vision and provided written informed consent prior to the experiment, based on a protocol approved by the Institutional Review Board of the University of California, Riverside. No participant was excluded from data analysis. Data of the current study are available online via the Open Science Framework, <https://osf.io/23brv/>.

Apparatus and Stimuli

The experiment was conducted in a moderately lit windowless room with a background luminance of about 500 lx. A video-based EyeLink 1000 (SR Research Ltd., Ontario, Canada) eye tracker recorded eye movements and pupil size at a sampling rate of 500 Hz. The EyeLink 1000 assesses gaze position by measuring the reflection of an infrared illuminator on the cornea

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with a video camera sensitive to light in the infrared spectrum. The eye tracker also records the size of the pupil in an arbitrary unit (AU) that is linearly associated with absolute pupil diameter. Visual stimuli were controlled by Psychtoolbox in Matlab (Mathworks, Boston, MA). These visual stimuli were presented on a 60-Hz LCD monitor (calibrated with an X-Rite I1Pro spectrophotometer) with a gray background (42 cd/m^2) at a fixed viewing distance of 80 cm, determined by the distance between the computer monitor and a chin set used to stabilize participants' head position. Auditory stimuli were presented via noise-canceling headphones at a constant loudness level of a Mac desktop computer (Apple, Cupertino, CA). Specifically, at the beginning of the study, participants listened a few demo sounds (not used in the experiment) and adjusted the loudness level (starting at 50% of the maximum loudness level) to their comfortable level (with a minimal setting at 25% of the maximum loudness level). Afterwards, this loudness level was kept constant throughout the experiment within each participant. We also calibrated the eye tracker based on the default 9-point calibration scheme set by EyeLink 1000. In this process, participants fixated a series of nine fixation targets on the display monitor, and gaze locations were recorded. We validated these measures against a second sequence of nine fixation targets. If the latter indicated a drift correction error of more than 1° of visual angle, this procedure was repeated until calibration was satisfactory. This procedure was carried out at the beginning of the experiment, when eye-tracking quality reduced during the study, or when the participants changed their sitting position after a break.

Emotional Sounds. Forty-eight 6-second sound clips were selected from the IADS (see Supplementary Table S1 for the indices of the chosen stimuli). Half of these sound clips are moderately arousing with a negative valence, such as sounds from screams, crying babies, explosions, etc. The remaining half of the sound clips are emotionally neutral, which include

everyday sounds, such as running water, a ticking clock, typewriting, etc. These neutral sounds have an average normative valence rating close to the central point of a 9-point valence scale (mean, interquartile range, IQR: 5.10, IQR: [4.48, 5.41]). In contrast, the negative sounds have much more negative valence rating (3.29, IQR: [3.04, 3.66], $p < .0001$, Wilcoxon signed-rank test). Furthermore, the negative sounds have higher arousal (6.18, IQR: [6.08, 6.36]) relative to the neutral sounds (4.43, IQR: [4.14, 4.65], $p < .0001$, Wilcoxon signed-rank test) on a 9-point arousal scale (Bradley & Lang, 2007).

Stimuli for Visual WM Task. The memory array for the visual WM task consisted of 4 distinct colors randomly chosen, with at least 24° from each other, from 180 colors that were evenly distributed on a circle in the Commission Internationale de l'Eclairage (CIE) Lab color space (see Zhang & Luck, 2008 for details). These 180 colors had equal luminance and varied mainly in hue and slightly in saturation. The memorability of these 180 colors across participants did not differ significantly between emotion conditions (Supplementary Figure S2; see a procedure of estimating stimulus memorability in Xie et al., 2020). The 4 studied colors on each trial were presented in squares ($1.4^\circ \times 1.4^\circ$ of visual angle) at locations randomly selected from 4 possible locations that were equally spaced on an invisible circle with a radius of 4.3° of visual angle. The consolidation-masking stimuli consisted of four masking patterns at the original locations of the memory items. Each masking pattern ($1.6^\circ \times 1.6^\circ$ of visual angle) consisted of four colored squares ($0.8^\circ \times 0.8^\circ$ of visual angle) in a 2×2 arrangement (Xie & Zhang, 2017a). The colors of these squares were randomly selected without repetition from the 180 colors except for the ones used for study and test. The test array contained one color square and three empty square placeholders (each $1.4^\circ \times 1.4^\circ$ of visual angle in size) at the original locations of the memory items. The presented color square contained a color that was either the same as (*no-*

change trials) or different from (*change* trials) the corresponding memory color at the same location in the memory array. The change and no-change trials were equally likely. On change trials, the new color was randomly sampled from the 180 colors, with at least 40° difference from the corresponding color from the memory array and with at least a 24° difference from other others in the memory array.

Procedure

Visual WM Task. As shown in Figure 2, each trial began with a 1,000 ms fixation display with a static central fixation circle ($\sim 0.1^\circ$ of visual angle in diameter) followed by a 6-second IADS sound clip. Subjects were instructed to fixate at this central circle while listening to the sound clip. Four seconds after the onset of the sound, the central fixation circle increased in size from 0.1° to 0.15° and then to 0.2° of visual angle in diameter for 100 ms, 100 ms, and 200 ms, respectively, to prepare participants for the upcoming WM task. After this dynamic central fixation display, the memory array containing 4 color squares was presented on the screen for 83.3 ms. In the consolidation masking conditions, pattern masks were presented after the memory array at two different SOAs: 100 ms (short SOA condition) or 333 ms (long SOA condition). After a delay interval with a fixed memory-and-test SOA of 1000 ms, a test display with 1 color square at the location of a previous memory item was presented until response. In half of the trials, the test color would be identical to the color at the same location in the memory display (“*old*”). In the other half of the trials, the test color would be a new color (“*new*”). Participants were instructed to report whether the test color was “*new*” or “*old*” by clicking corresponding boxes presented below the test display with a computer mouse (see Figure 2). No feedback was provided for this response. In the no-mask condition, all the timing parameters and

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test procedures were identical to those in the consolidation masking conditions, except that no pattern masks were presented during the retention interval.

Immediately following the visual WM change detection response, participants were presented with the arousal and then the valence Self-Assessment Manikin (SAM) 9-point scales (Bradley & Lang, 1994) along the horizontal meridian of the screen (see Figure 2). Participants used the computer mouse to click on the scales to evaluate the arousal and valence of the sound clip presented at the beginning of the trial. Although participants' ratings on these scales tend to be highly consistent for emotion stimuli within a given emotional category (Xie & Zhang, 2016a, 2017c, 2018), these ratings can still provide estimates of subjective emotional experiences and also enforce the subjects to process the emotional stimulus presented at the beginning of the trial to maximize the potential interaction between induced emotional experience and cognitive task performance (Xie & Zhang, 2016b).

The emotional conditions (negative/arousing vs. neutral/non-arousing) of the sounds were organized into 2-trial mini-blocks (the same emotional condition with different IADS stimuli was repeated over two consecutive trials). Other experimental factors, including change or no-change of the test color and the masking conditions (short SOA, long SOA, and no-mask), were randomly intermixed. Participants completed a total of 192 trials with 96 trials for each emotion condition. We randomly split these trials into 6 blocks of 32 trials with the constraint that the emotional conditions were balanced within each block (16 negative trials and 16 neutral trials). With this constraint, it was possible that other experimental factors were not balanced across blocks; yet the combination of experimental factors were in principle random across blocks and across participants.

Measures of Individual Differences. Following the experimental task, participants filled out a demographic survey and a package of self-report questionnaires capturing their early-life stress and neglect during childhood, as well as their recent mood states using the Patient Health Questionnaire-9 (PHQ-9) and the Generalized Anxiety Disorder-7 (GAD-7) scales. As shown in previous research, ACEs should be correlated with neglect during childhood, depressed mood, and anxious feelings (Anda et al., 2006; Dong et al., 2003; Lee et al., 2020; Michl et al., 2013).

ACEs. This questionnaire, adopted from Anda and colleagues (2006), measures childhood exposure to abuse and family dysfunction experienced by respondents before the age of 18 years. Responses are reduced to 8 ACE categories: emotional abuse, physical abuse, sexual contact abuse, exposure to alcohol or other substance abuse, mental illness, violent treatment of mother or stepmother, criminal behavior in the household, and parental separation or divorce (Anda et al., 2006). The numbers of ACEs are summed to create a total ACE score (range: 0–8, Cronbach’s alpha = 0.80). At the end of the ACE questionnaire, we included a 10-item questionnaire (Dong et al., 2003) capturing emotional neglect (e.g., “*There was someone in my family who helped me feel important or special.*”) and physical neglect (e.g., “*I didn’t have enough to eat.*”) to verify the ACE measure. Participants report to what extent they agree with statements in the questionnaire on a 5-point Likert scale. The total score of neglect ranges from 10 to 50 (Cronbach’s alpha = 0.69).

PHQ-9. This a self-report measure of depressive symptoms over the previous two weeks (Kroenke et al., 2001). Participants respond to 9 descriptions of depression-related symptoms by indicating how often in the past two weeks they have been bothered by these symptoms using a 4-point scale (from “*Not at all* = 0” to “*Nearly Every Day* = 3”). Possible scores range from 0-27 (Cronbach’s alpha = 0.82), with a higher score indicating more depressed symptoms.

GAD-7. This is a self-report questionnaire for screening and severity measure for generalized anxiety (Spitzer et al., 2006). It has seven items, which measures the severity of various signs of generalized anxiety on a 4-point scale (from “*Not at all* = 0” to “*Nearly Every Day* = 3”). Larger values represent higher levels of anxiety. Possible scores range from 0 to 21 (Cronbach’s alpha = 0.89).

Data Analysis

Visual WM Measures. Participants’ performance in the visual WM change detection task was assessed as Cowan’s K (set size $\times$ [hit rate – false alarm rate]), which indicates the number of remembered stimuli (Rouder et al., 2011). We obtained several measures from these Cowan’s Ks across conditions. First, the storage capacity of visual WM was estimated based on the K in the no-mask condition. Second, we calculated the difference in Ks between long and short SOA conditions as an estimate of WM consolidation speed (Xie & Zhang, 2017b). Third, as a complementary measure of WM consolidation speed, we also estimated the ratio between the mean increase in K across short and long SOA conditions and the mean increase in K across short and no-mask conditions, namely $(\text{long} - \text{short}) / (\text{no-mask} - \text{short})$, across participants. This corrected estimate tells us the proportion of encoded WM items from short to long SOA conditions, relative to the lower and upper bounds of task performance set by the short SOA and no-mask conditions. Conceptually, this is equivalent to a measure of consolidation efficiency, in that a faster WM consolidation speed should lead to more items encoded into WM (Vogel et al., 2006), hence a greater proportion of encoded items at the later phase of WM consolidation captured by the long SOA condition. Similar metric has been used to quantify the efficiency in cognitive control (see further details in Vogel, McCollough, & Machizawa, 2005). Overall, we

observed highly consistent experimental findings based on these different measures of WM task performance.

Pupil Data. The pupil data were prepared and analyzed using methods established in previous studies (Granholm et al., 1996; Siegle et al., 2004). As shown in Figure 2A, a 4,600-ms epoch (-200 ms to 4,400 ms relative to the sound onset) was used for pupil size measures. Artifacts, including blinks, were identified and rejected/corrected using established algorithms (Siegle et al., 2003, 2004). In brief, a linear interpolation was applied to the rest of the trials with blinks for blink correction. Additional 100-ms buffer data preceding and following the measurement epoch were included in this procedure to minimize edge artifacts in the delinking algorithm (Siegle et al., 2004). Trials with eye blinks at the beginning and at the end of a trial or composed of more than 50% interpolated area within the measurement time window were rejected from further analyses. The trial-by-trial de-blinked buffer-removed pupil size data were then normalized and corrected for baseline fluctuations (-200 ms to stimulus onset) to allow for comparison of phasic pupil responses across participants. Overall, 159 (± 27) trials (out of 192 trials) on average were retained for pupil size analysis for each participant (80 ± 13 vs. 79 ± 14 for negative and neutral conditions, respectively). Of primary interest, arousal responses were measured as the extent of pupil dilation following the presentation of IADS sounds between 2000 ms to 4000 ms post sound onset. This time window was selected to capture pupil dynamics under the IADS stimuli at least 1000 ms prior to the WM task (see Figure 2). It is thus unlikely to be contaminated by preparatory eye blinks due to transition of task event, pupillary light reflex due to the presentation of WM task stimuli, or evoked pupil responses related to the cognitive effort associated with the WM task (Alnaes et al., 2014; Hess & Polt, 1964). This pupil measure

is reliable across participants based on a split-half analysis as demonstrated in Supplementary Figure S1 (mean $r = 0.83$ for both the negative and neutral conditions across 1000 iterations).

Statistical Procedures. We adopted conventional within-subject statistical procedures (e.g., repeated-measures analysis of variance [ANOVA], and paired t -test) to evaluate the differences in WM task performance and pupil size measures across experimental conditions, along with their effect size estimates. To probe the *a priori* individual differences, we split the subjects into groups based on theoretical or empirical cut-off scores from prior research. We evaluated the contributions of these individual differences to WM task performance under induced negative arousal after controlling for other factors based on repeated-measures analysis of covariance (ANCOVA). We also verified these results using repeated-measures correlation, namely r_{rm} (Bakdash & Marusich, 2017) and mixed-effect regression analyses (see Supplementary Online Materials). Here, it should be noted that while the current sample size is adequately powered to detect the focal experimental effect of induced negative arousal on WM consolidation speed, the statistical power available for moderation analyses of individual differences in experimental outcomes is attenuated.

Complementary to these conventional statistical tests, we supplied these observations with non-parametric or resampling statistics. For instance, to account for the impact of restricted range in the subjective rating scores across subjects, we used rank-based statistics to evaluate their differences across conditions (e.g., Wilcoxon signed-rank test) and their associations with other variables (e.g., Spearman rank-order correlation, Bishara & Hittner, 2015). In resampling analyses (Good, 2013), we compared the observed data against the empirically derived null distribution created by shuffling condition labels within each participant 10,000 times. The obtained p values (two-tailed, unless specified) represent likelihood of the observed findings if

there were no true differences across conditions. It is worth noting that because these non-parametric or resampling approaches pose minimal assumptions on the data and analytical procedure, these methods mitigate potential statistical artifacts, if any, emerging from the violation of some parametrical statistical assumptions (e.g., normality or homogeneity, Good, 2013).

Results

Manipulation Check: Effectiveness of Induced Negative Arousal

As shown in Figure 3A, participants' pupil sizes were generally larger under the negative condition as compared with the neutral condition. This observation was supported by a significant difference in the average pupil size between 2,000 ms and 4,000 ms following the onset of IADS sound clip between negative and neutral conditions ($t_{(119)} = 6.95$, $p < .0001$, Cohens' $d = 0.63$, 95% Confidence Intervals: [0.44, 0.83]; Figure 3B). This observation is consistent with the previous findings that negative arousing auditory stimuli elicit greater pupil dilation (e.g., Partala & Surakka, 2003). Furthermore, participants' subjective ratings for the sound clips following the visual WM task also showed more negative valence and higher arousal for the negative sounds as compared to neutral sounds (Wilcoxon signed-rank tests, $ps < .0001$; Figure 3C). In addition, the objective measure of arousal using the windowed pupil size was significantly correlated with subjective reports of arousal separately in the negative condition ($\rho = .33$ [.16, .48], $p = .00027$) and in the neutral condition ($\rho = .20$ [.02, .37], $p = .029$). As a complementary test, across conditions, these within-subject measures of objective and subjective aspects of induced arousal were also significantly correlated with a medium-to-large effect size based on repeated-measure correlation ($r_{rm} = .44$ [.29, .58], $p < .0001$; Figure 3D). Overall, these

results suggest that the current emotion induction procedure with the selected IADS stimuli can subjectively and objectively induce negative arousal.

WM Task Performance Under Induced Negative Arousal

Overall, participants' performance in the visual WM task followed the typical time course of WM consolidation observed in previous studies (Ngiam et al., 2019; Vogel et al., 2006; Xie & Zhang, 2017a). In principle, participants' performance in the visual WM task in terms of Cowan's K should be positive ranging from 0 to memory set size. However, because of measurement noise, the measure of Cowan's K could yield a value slightly negatively deviated from 0 (e.g., -0.5). In the current study, 16 participants showed this pattern in the short-SOA condition, however, it did not demonstrate a systematic difference between the emotion conditions (Wilcoxon signed-rank test: $p = .27$; see cumulative probability curves, Figure 4B). Here, we reported results separately for all participants ($n = 120$) and for those with above-zero Cowan's Ks ($n = 104$). As shown below, both analyses yield highly consistent findings.

First, for all 120 participants recruited for the study, the number of retained WM representations increased as the amount of time allowed for WM consolidation increased (Cowan's K from short to long SOA conditions: 1.08 ± 0.68 to 2.00 ± 0.61 , Cohen's $d = 1.37$ [1.11, 1.62]; Figure 4A). This observation was supported by a significant main effect of masking condition in a 2 (masking condition: short vs. long SOA) by 2 (emotion condition: negative vs. neutral) repeated-measures ANOVA on Cowan's K ($F_{(1, 119)} = 225.05, p < .0001, \eta_p^2 = .65$). Of primary interest, we found a significant interaction effect between masking and emotion conditions across all subjects ($F_{(1, 119)} = 4.91, p = .029, \eta_p^2 = .04$; Figure 4A), while the main effect of emotional condition was not statistically significant ($F < 1$). This interaction effect was driven by significantly more items encoded into WM at the long SOA condition under negative

arousal (negative vs. neutral: 2.07 ± 0.74 vs. 1.91 ± 0.70 , $t_{(119)} = 2.29$, $p = .024$, Cohen's $d = 0.21$ [$0.03, 0.39$]), but not at the short SOA condition (negative vs. neutral: 1.04 ± 0.83 vs. 1.12 ± 0.79 , $t_{(119)} = 1.03$, $p = .30$, Cohen's $d = -0.09$ [$-0.27, 0.09$]). These observations are also in line with a faster consolidation speed estimated by the difference score of Cowan's K between long- and short-SOA conditions under induced negative arousal (negative and neutral: 1.03 ± 0.92 vs. 0.79 ± 0.87 , $t_{(119)} = 2.22$, $p = .029$, Cohen's $d = 0.20$ [$0.02, 0.38$]). Participants' WM capacity estimate at the no-mask condition, however, did not significantly differ across emotion conditions (negative vs. neutral: 2.40 ± 0.81 vs. 2.40 ± 0.79 , $t_{(119)} = -0.03$, $p = .98$, Cohen's $d = -0.003$ [$-0.18, 0.18$]). Second, for the 104 participants who showed above-zero Cowan's K measures, we obtained highly consistent results as those from the full sample. Again, there was a significant main effect of masking ($F_{(1, 103)} = 176.61$, $p < .001$, $\eta^2_p = .63$) and a significant interaction effect between masking and emotion condition on Cowan's K measures ($F_{(1, 103)} = 9.36$, $p = .003$, $\eta^2_p = .08$). And participants' performance in the no-masking condition was also comparable between the negative and neutral conditions ($t_{(103)} = -0.30$, $p = .77$, Cohen's $d = -0.03$ [$-0.22, 0.16$]).

Could the significant interaction between masking manipulation and emotion conditions result from the potential floor effects on restricted Cowan's K values in the short-SOA conditions? This does not seem to be case for the current study. First, Cowan's K distribution in the short-SOA condition followed a similar shape as those in the long-SOA and no mask conditions (Figure 4B). Next, to ensure that mean estimates depart sufficiently from the middle of a measurement scale with reasonably equal variance across experiment conditions, we applied arcsine transformation (Cohen et al., 2013) to Cowan's K measures proportional to set size (0 to 1 in replace of 0 to 4 items, respectively). Of primary interest, we found that there was still a

significant interaction effect between masking and emotion condition in these arcsine-transformed Cowan's K measures in all 120 participants ($F_{(1, 119)} = 4.90, p = .029, \eta^2_p = .04$) and in the 104 participants with above-zero Cowan's K measures ($F_{(1, 103)} = 9.35, p = .0028, \eta^2_p = .08$). Furthermore, there was no significant difference in these arcsine-transformed Cowan's K measures in the no-mask in either case ($ts < 1$). Considering the consistency in the statistical results of participants' performance in the full sample and the reduced sample with raw or transformed Cowan's K measures, in later analyses, we will primarily report the results from the full sample based on raw Cowan's K.

Finally, as a complementary test, we also examined participants' WM consolidation speed after correcting for upper and lower bound of task performance set by the no-mask and short SOA conditions, namely (long –short) / (no-mask – short). This measure takes into account participants' performance in all three conditions all at once, and hence would minimize assumptions imposed on statistical tests. We estimated this measure across Cowan's K distributions of different experimental conditions (Figure 4B & 4C) and compared the group average measure against the null distribution established by shuffling the emotion condition labels 10,000 times while retaining the SOA condition labels (Good, 2013). This treatment retains the SOA effects within each subject, allowing us to isolate the effect of induced negative arousal on WM task performance. Furthermore, as this analysis is focused at the group level across different random shuffles of the data, the observed findings would therefore be robust against measurement noise at the individual level (Good, 2013). If WM is immune to emotional influences, it is expected that the observed corrected estimate of consolidation speed across emotion conditions should be statistically non-distinguishable from the null distribution derived from shuffled emotional condition labels. In contrast to this prediction, we found that

participants encoded more items into WM in the long SOA condition after taking into account the lower and upper bounds of task performance (negative vs. neutral: 76% vs. 62%, difference: 14% [1%, 28%], permutated $p = 0.036$; Figure 4C).

Collectively, these converging findings across different analytical procedures indicated faster WM consolidation under induced negative arousal, even though WM storage capacity estimates remain comparable across emotional conditions. These effects remain robust across different estimation metrics of WM consolidation speed. It is noted that the significant emotion effect on WM consolidation speed was small in size overall (Cohen's $d \sim 0.20$) based on Cohen (1992). We next investigate factors that could potentially moderate the size of this effect across participants.

Exploratory Analysis: Individual Differences as Moderators of Experimental Effects

Effectiveness in Arousal Induction. The distribution of induced arousal based on the difference in pupil size measure across negative and neutral condition showed a large amount of variance across participants (Figure 5A). Specifically, some participants showed smaller induced pupil sizes in the negative condition as compared with the neutral condition, evident by negative values in the windowed pupil size difference between negative and neutral conditions. We then separated all participants into two groups using zero as the cut-off point. One group has showed effective arousal induction (i.e., larger induced pupil size in the negative versus neutral condition, $n = 88$), which is consistent with what would be predicted by the normative data. However, the other group has showed ineffective arousal induction (i.e., smaller induced pupil size in the negative versus neutral condition, $n = 32$), which is inconsistent with what the normative data would predict. We further examined participants' self-report arousal ratings. Although both groups reported similar arousal level for negative sounds (median of arousal

ratings for negative sounds: 5.51 vs. 5.73, Mann-Whitney U test, $Z = 0.62$, $p = .54$), the ineffective arousal induction group reported that the neutral sounds were subjectively more arousing as compared with the effective arousal induction group (median of arousal ratings for neutral sounds: 5.13 vs. 4.59, Mann-Whitney U test, $Z = 2.13$, $p = .033$). This finding suggests that a mere reliance on normative rating data is not sufficient for assessing the effectiveness of emotion induction, highlighting the importance to evaluate individual differences in laboratory studies of induced emotion.

We next examined how this individual difference influences participants' WM task performance under induced negative arousal, by comparing the experiment effects on Cowan's K between the effective versus ineffective arousal induction groups (Figure 5A). We found that WM consolidation speed estimated by the difference in Cowan's K between long and short SOA conditions was significantly faster in the negative relative to the neutral condition, primarily in the effective arousal induction group (negative vs. neutral: 1.15 ± 0.86 vs. 0.73 ± 0.81 , $t_{(87)} = 3.62$, $p = .00049$, Cohen's $d = 0.39$ [0.17, 0.60], Figure 5B), but not in the ineffective arousal induction group (negative vs. neutral: 0.71 ± 1.01 vs. 0.95 ± 0.98 , $t_{(31)} = 0.98$, $p = .38$, Cohen's $d = -0.17$ [-0.52, 0.18], Figure 5D). This between-group difference was supported by a significant 2 (arousal induction: effective vs. ineffective) by 2 (masking: short vs. long SOA) by 2 (emotion arousal: negative vs. neutral) interaction effect in ANOVA on Cowan's Ks ($F_{(1, 118)} = 7.40$, $p = .008$, $\eta^2_p = .059$). This interaction effect remain statistically significant in ANCOVA after taking into account the covariance attributed to ACEs, depressed mood, anxious feelings, and gender ($F_{(1, 114)} = 9.02$, $p = .003$, $\eta^2_p = .073$). These observations are also supported by mixed-effect regressions as shown in Supplementary Table S2.

When the corrected WM consolidation speed measure was used, namely (long –short) / (no-mask – short), we also found that participants in the effective arousal induction group encoded more items into WM at the long SOA conditions under induced negative arousal (negative vs. neutral: 82% vs. 56%, permutated $p = .0032$; Figure 5C). In contrast, participants in the ineffective arousal induction group did not show this pattern (negative vs. neutral: 59% vs. 73%, permutated $p = .34$; Figure 5E). Critically, this consolidation speed effect was significantly different between these two groups of participants (permutated $p = .022$; Figure 5F).

Importantly, the relationship between the magnitude of induced arousal captured by pupil size and the size of consolidation speed effect between emotional conditions was not limited to the median split of the participants into the effective versus ineffective arousal induction groups. This effect also manifested as a significant correlation between the difference in induced pupil size between emotional conditions and the consolidation speed measure between emotional conditions across participants (negative – neutral, $r = .24$ [.06, .40], $p = .009$; Figure 6A). This correlation remained robust when we assessed repeated-measures correlation between consolidation speed and induced pupil size without taking the difference between negative and neutral conditions ($r_{rm} = .30$ [.13, .46], $p = .00072$; Figure 6B). In contrast, there was no significant association between induced pupil size and Cowan’s K in the no-mask condition (negative – neutral, $r = -.06$ [-.24, .12], $p = .49$; $r_{rm} = -.06$ [-.24, .12], $p = .52$; Figure 6C & 6D). This was unlikely an issue of insensitive WM capacity measure in the current study, because Cowan’s K at the no-mask condition under neutral emotion was significantly correlated with sub-clinical depressed mood (PHQ-9 scores below than 20, Kroenke & Spitzer, 2002; $r = -.19$ [-.36, -.004], $p = .045$), similar to previous observations from fully separate samples (Xie, Berry, Lustig, Deldin, & Zhang, 2019; Xie, Cappiello, Park, et al., 2018). Overall, these findings

suggest that induced negative arousal primarily speeds up visual WM consolidation, and that this effect is moderated by individual differences in induced negative arousal. The more effective arousal induction is, the faster WM consolidation speed is under negative arousal.

The significant amount of within- and between-subject variance in the experimental outcomes accounted for by pupil size measures, however, could only be partly reproduced based on self-report arousal rating data. In general, self-report affective responses were consistent with pupil measures in revealing the relative arousal difference between negative and neutral sounds within participants (Figure 3D). Consistent with this observation, repeated-measure correlation analyses showed that self-report arousal ratings were also significantly correlated with the experimental estimates in WM consolidation speed between negative and neutral conditions ($r_{\text{rm}} = .21$ [.03, .38], $p = .019$; Supplementary Figure S3). However, across participants, the difference scores in self-report arousal responses between negative and neutral conditions were not significantly correlated with the experimental effects on WM consolidation speed between emotion conditions ($r = .09$ [-.09, .26], $p = .31$; Supplementary Figure S3). As a result, split-group analyses based on a median split of self-report rating data (negative – neutral) did not reveal a significant difference in experimental outcomes between those who responded more strongly to negative sounds as compared with those who were more indifferent about the affective values of the sounds (interaction effect for emotion conditions, SOA, and median-split arousal rating groups on Cowan's K: $F_{(1, 118)} = 2.68$, $p = .11$, $\eta^2_p = .022$). Together, these results suggest that self-report ratings, while accounting for a significant amount of within-subject variance in experimental outcomes, may not be sufficient to capture between-subject variation in the effects of induced negative arousal on WM task performance.

ACEs. In the current sample, we observed a higher percentage of participants falling into the category of higher ACEs (total score ≥ 4 , 20.8%, $\chi^2_{(1)} = 7.62$, $p = .007$), in comparison with a population-based norm for the San Diego County of California (12.5% of the samples based on Anda et al., 2006). This pattern was consistent with our previous survey of 188 non-overlapping participants in the same region (18%, separated by 1.5 years at the time of data collection). As summarized in Supplementary Table S3, the ACE total score was significantly correlated with self-report childhood neglect ($r = .34$ [.17, .49], $p = .00015$), depressed mood ($r = .40$ [.24, .54], $p < .0001$) and anxious feeling ($r = .21$ [.03, .37], $p = .025$), suggesting high convergence validity of the ACE measure in the current study as compared with previous studies (Anda et al., 2006; Lee et al., 2020; Michl et al., 2013). Yet, the total score of ACEs was not statistically significantly associated with the overall magnitude of induced negative arousal measured by pupil size or subject ratings of affective responses between emotion conditions (see Supplementary Table S4 for details), similar to the findings of a previous study (Pieritz, Rief, & Euteneuer, 2015). That said, we found that certain sub-component of ACEs was significantly correlated with greater induced arousal, as summarized in Supplementary Table S5.

We next examined how ACEs relate to WM consolidation process under induced negative arousal, by comparing the experimental effects on Cowan's K between participants with high versus low ACEs (Supplementary Figure 4A) based on the population-based cut-off score of 4 (top 12.5% of the norm, Anda et al., 2006). We found that WM consolidation (K difference between long vs. short SOA conditions) was significantly faster in the negative condition relative to the neutral condition in the high ACEs group (negative vs. neutral: 1.44 ± 1.06 vs. 0.62 ± 0.83 , $t_{(24)} = 3.44$, $p = .002$, Cohen's $d = 0.69$ [0.25, 1.12], Supplementary Figure 4B), but less so in the low ACEs group (negative vs. neutral: 0.92 ± 0.86 vs. 0.84 ± 0.88 , $t_{(94)} = 0.76$, $p = .45$, Cohen's d

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= 0.08 [-0.12, 0.28], Supplementary Figure 4D). This between-group difference was supported by a significant 2 (ACEs: high vs. low) by 2 (masking: short vs. long SOA) by 2 (emotion arousal: negative vs. neutral) interaction effect in ANOVA on Cowan' Ks ($F_{(1,118)} = 7.80, p = .006, \eta^2_p = .062$). This interaction effect remained statistically significant after we took into account effectiveness in arousal induction (effective vs. ineffective), depressed mood, anxious feelings, and gender in ANCOVA ($F_{(1,113)} = 7.70, p = .006, \eta^2_p = .064$; see Discussions for a caveat in this ANCOVA). However, we did not observe a significant interaction effect among emotion manipulation, SOA condition, effectiveness of arousal induction, and ACEs on WM measures ($F < 1$). These observations also hold when we adopt the regression approach as shown in Supplementary Table S2.

As a complementary analysis, we found that high ACEs participants encoded more items into WM in the long SOA condition under induced negative arousal, based on the corrected WM consolidation speed estimate (negative vs. neutral: 94% vs. 51%, permuted $p = .0040$; Supplementary Figure 4C). In contrast, low ACEs participants did not show a significant pattern (negative vs. neutral: 71% vs. 64%, permuted $p = .42$; Supplementary Figure 4E). This difference between these two groups of participants was also statistically significant (permuted $p = .026$; Supplementary Figure 4F). These findings suggest that the compound measure of ACEs is also a significant moderator of the experiment effects of induced negative arousal on WM consolidation speed (also see Supplementary S5 for more details). These exploratory findings entail further replication with independent estimates of these effect sizes based on a different participant cohort and in a larger sample of participants with ACEs.

Discussion

The present study shows that induced negative arousal can facilitate moment-by-moment information encoding in WM, manifested as faster WM consolidation speed, without affecting WM storage capacity. The size of this effect is moderated by individual differences in the effectiveness of arousal induction and the observers' early-life stress. Participants who are more sensitive to negative IADS sounds or have more ACEs show faster WM consolidation speed under induced negative arousal. These effects remain robust when other individual differences in the current mood states and gender are taken into consideration. Our results add several novel perspectives into the theoretical understandings of the complex relationship between emotion and WM (Baddeley, 2012b) and between WM consolidation and storage capacity (Bundesen, 1990). Furthermore, by identifying the key moderators of our experimental observations, our findings move beyond the binary view of experimental effects (Rubin, 1992) and highlight the importance of assessing individual differences in the research of emotion and WM.

Emotional Influences on WM are Time-dependent

By showing that induced negative arousal exerts a significant impact on the WM consolidation process, our findings highlight that WM is not immune to emotional influences, even when the emotional context is irrelevant to WM task contents (Souza et al., 2020). Instead, the presence or absence of emotional influences on WM task performance may be contingent on when WM task performance is assessed (e.g., Long et al., 2020). Theoretically, when WM consolidation process is interrupted by random pattern masks during the consolidation process, more items should be encoded into WM as memory-and-mask SOA increases in a condition where WM consolidation is faster (Blalock, 2015; Ngiam et al., 2019; Xie & Zhang, 2017b, 2018a). The current finding that more items are encoded into WM in the long SOA condition

under induced negative arousal, either with or without correcting for participants' task performance in the short SOA and no-mask conditions, supports the prediction that induced negative arousal can speed up WM consolidation. Yet, when the WM consolidation process is not interrupted by masking during a brief retention interval, observers remember comparable numbers of items in WM between negative and neutral conditions. These observations are in line with the predictions summarized in Figure 1A (vs. 1D). Furthermore, these findings also refute the predictions that induced negative arousal would lead to an overall boost in task performance at any time points during WM consolidation, either with or without an expanded WM capacity (Figure 1B and 1C). Collectively, our findings may account for some inconsistencies in the literature regarding the effects of emotion on the number of retained WM items. That is, probing observers' WM task performance too early or too late during the delay interval may yield only a modest emotional effect on WM task performance.

How does this consolidation speed effect relate to the impact of induced negative arousal on WM precision (e.g., Long et al., 2020)? Our current study was not designed to examine the time course of induced negative arousal on WM precision and hence could not directly address this issue. That said, based on a recent finding (Long et al., 2020), it is possible that induced negative arousal can additionally lead to a strategic trade-off between the number and precision of retained WM representations when more time is allowed for WM consolidation. That is, as participants encode more items into WM, they could trade the number of retained WM items for higher WM precision (Ye et al., 2019), within their limited WM storage capacity (Zhang & Luck, 2008, 2011). Consequently, WM precision is higher under induced negative arousal at a later phase of WM consolidation even though this may be at the cost of a reduced number of retained WM items (also see Spachtholz et al., 2014). However, this strategic trade-off may not

reflect a real boost of induced negative arousal on WM representations (see some discussions in Xie & Zhang, 2016a). Furthermore, the trade-off revealed by the continuous recall paradigm (Zhang & Luck, 2008) may not directly predict the current compound measure of WM change detect task performance (e.g., Barton et al., 2009; Xie & Zhang, 2017; Zhang & Luck, 2008). To address these issues, future research should investigate the fidelity of encoded WM representations over time under different emotional contexts.

WM Consolidation Speed and Storage Capacity are Dissociable by Negative Arousal

Our data also provide strong support for the theoretical dissociation between WM consolidation process and its storage capacity. Although some theoretical and mathematical models have considered processing speed and storage capacity as independent limits of WM (e.g., Bundesen, 1990), others argue that processing speed is a more fundamental limit than WM storage capacity (e.g., Alvarez & Cavanagh, 2004; Cavanagh, 1972; Hulme, Thomson, Muir, & Lawrence, 1984). The latter is supported by the observations that the increase in processing speed as a function of training (Hulme et al., 1991, 1995), familiarization (Ngiam et al., 2019), or development (Kail, 1992) can also lead to an increase in the number of items one can remember in WM. However, as discussed in some previous studies (Ngiam et al., 2019; Xie & Zhang, 2017b, 2018a), these concurrent effects on WM processing speed and storage capacity under certain task manipulations can occur if WM consolidation process is disrupted before it completes (e.g., short presentation time or masking). Indeed, using both behavioral and EPR measures, Xie and Zhang (2017b, 2018a) have shown that stimulus familiarity can speed up visual WM consolidation speed without significantly influencing WM capacity. Our observation of faster WM consolidation with intact WM storage capacity under induced negative arousal

adds another piece of evidence favoring the independence between WM consolidation speed and storage capacity.

Individual Differences Moderate Emotional Effects on WM

Furthermore, by examining individual differences, this study reveals the role of subject-level factors in the interaction between emotion and WM, including the effectiveness of induced arousal and early-life stress. Although these factors are related, they are conceptually and empirically separable from one another (e.g., Pieritz, Rief, & Euteneuer, 2015). In the current study, we have also failed to observe a significant association between the effectiveness of arousal induction and the compound measure of ACEs. That said, we find that certain aspect of ACEs (childhood sexual contact) is significantly correlated with the magnitude of induced negative arousal (Supplementary Table S5). This observation is consistent with the two-dimension model of ACEs (McLaughlin et al., 2016). According to this model, threat-related ACEs such as physical and sexual abuse can lead to generalized threat responses to a wide range of stimuli. In contrast, ACEs associated with deprived early environments such as neglect and poverty are less sensitive to negative arousing events (McLaughlin et al., 2014).

While the effectiveness of arousal induction and early-life stress significantly moderate the experimental effects of induced emotion on WM, they are often neglected in previous research. Without considering these key individual differences, smaller effect sizes in some studies may lead to a conclusion that WM is immune to any emotional influences (Souza et al., 2020). By showing that these factors systematically moderate the size of experimental findings of induced negative arousal on WM, our data highlight the importance to move from a binary view on experimental outcomes to a focus on the effect size profile in experimental studies (Rubin, 1992). Ultimately, it is the effect size that characterizes the relevance of an experimental

observation. Considering the core roles of WM in human cognition, delineating the conditions under which emotion would exert a greater impact on WM may therefore facilitate the broader research effort to understand the relationship between emotion and cognition.

Caveats and Future Directions

Several aspects of the study should be noted. First, the current behavioral effect of induced negative arousal on WM consolidation speed is presumably supported by the engagement of adrenergic system in the central nerve system, given the close association between pupil size and the rapid change in cortical adrenergic activity in animal models (e.g., Liu et al., 2016). However, how norepinephrine activity is rapidly involved in the distributed neural system underlying information processing in WM in humans (Eriksson et al., 2015) remains to be clarified (see Dash, Moore, Kobori, & Runyan, 2007; Motley, 2018 for some discussions on this issue). Considering the critical role of norepinephrine in prioritizing information processing under the focus of attention (Mather et al., 2016), future research should therefore specify the spatial and temporal profiles of adrenergic involvement during WM processes (Chamberlain et al., 2006).

Second, our findings on the positive relationship between pupil size and visual WM consolidation speed (Figure 6) raise an intriguing possibility that more sensory inputs under a larger pupil could facilitate the process of visual WM consolidation¹. This hypothesis is consistent with the theoretical perspective of “active vision,” which takes into account not only the reflective but also the information-control functions of the visual system (Findlay & Gilchrist, 2003). As a preliminary assessment of this idea, we focused on neutral trials to

¹ We would like to thank Dr. Brandon J. Schmeichel for suggesting this intriguing idea.

minimize the impact of induced emotional experience on WM. We failed to observe a significant correlation between windowed pupil size measure and WM consolidation speed under the neutral condition ($r = -.003 [-.18, .18], p = .97$). Yet, our current data may not be able to offer a direct test for the proposed hypothesis, considering that our windowed pupil size measure was taken 1-second before the visual WM task. While this measure minimizes artifacts related to pupillary light reflex when color squares were presented on the screen and captures an observer's internal states before the visual WM task, it is temporally separate from WM encoding. To better examine the relationship between pupil size and visual WM while controlling for the impacts of arousal, future research may consider parametrically manipulating the ambient luminance levels of an experiment setting to adjust an observer's overall pupil size at the time of visual WM encoding. Likewise, to better access the impacts of arousal on WM, future research may consider using non-visual stimuli to minimize the potential influences of induced arousal on pupil-mediated visual processes.

Third, the current study has primarily relied on a behavioral measure of WM consolidation speed based on the difference score of WM task performance across different masking conditions (short vs. long study-and-mask SOAs, Vogel et al., 2006; Wilms et al., 2013). However, this measure may be a suboptimal estimate of WM consolidation speed, because the short encoding duration and the use of masking stimuli would interrupt the underlying WM consolidation process (see more discussions in Ricker et al., 2018; Xie & Zhang, 2018a). An alternative approach is to infer WM consolidation process based on the attention blink paradigm (Raymond et al., 1992). The idea is that compromised detection ("blink") of a second target (T2) after successful detection of the first target (T1) within a given time window during rapid serial visual presentation may reflect the temporal processing limit in consolidating

T1 into WM (Chun & Potter, 1995; Martens & Wyble, 2010; Ricker et al., 2018; Ricker & Hardman, 2017). However, this indirect inference of the WM consolidation process for T1 based on an observer's performance on T2 is not ideal either, because WM consolidation limit is not the only mechanism underlying attentional blink (see a review in Dux & Marois, 2009). For example, attentional blink could be related to the time limit in freeing up cognitive resources for distractor inhibition, which is a control-related process. Studies showing greater attentional blink under emotional influences (e.g., de Jong et al., 2010), therefore, could not serve as the direct evidence for the potential emotional impacts on WM consolidation process. This is because these findings may be attributed to the detrimental effects of negative arousal on control-related processes (e.g., Choi et al., 2013; Eysenck et al., 2007; Schoofs et al., 2008; Shackman et al., 2006). A better approach would be to more directly measure WM representations and processes without further interruptions based on ERPs, such as the Contralateral Delay Activity (e.g., Perez & Vogel, 2012; Vogel & Machizawa, 2004; Xie & Zhang, 2018a). Future research needs to leverage the strengths of this neural measure to delineate the temporal dynamics of WM consolidation under induced negative arousal (see further discussions in Xie & Zhang, 2021).

Fourth, the current study focused on negative arousal, whereas the effects of positive arousal on the WM consolidation process remain to be established. Our current findings have not distinguished arousal from negative valence and thus it is unclear whether negative valence is required for increased WM consolidation speed under increased arousal. A future experiment with an additional positive arousal condition would resolve this uncertainty. Several foreseeable issues are to be considered in this future study. Methodologically speaking, inducing positive arousal can be less effective in a laboratory setting, probably because positive affect, in general, tends to show larger variations as compared with negative affect within and across individuals

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(e.g., Hardy & Segerstrom, 2017). With certain emotional induction procedures (e.g., unexpected reward), positive arousal may be induced and subsequently facilitate WM task performance (e.g., Yang, Cook, & Isen, 2013). Conceptually speaking, however, additional mechanisms may be involved, other than the norepinephrine pathway, to support positive arousal (Hauser et al., 2019). It is therefore improper to consider positive arousal the same as, or the opposite of, negative arousal. Future research should therefore systematically assess the contributions of positive arousal to cognition by properly inducing positive arousal and assessing the neurobiological pathways underlying these potential effects.

Finally, we have found that early stressful life experiences captured by ACEs could increase observers' WM task performance under induced negative arousal after factoring out other affect-related characteristics, such as depressed mood and anxious feelings. A caveat of this analysis is that early-life stress and these negative mood states are conceptually and empirically correlated, such that statistical controlling for their covariance may affect its conceptual interpretation (Miller & Chapman, 2001). This issue is mitigated by a robust effect of early-life stress on experimental findings with or without covariance analysis. Furthermore, while our exploratory analysis reveals an often-neglected moderator effect of early-life stress and its facilitation of cognitive task performance under induced negative arousal, our data are insufficient to determine whether the boosted WM consolidation under induced negative arousal among high ACEs individuals is adaptive or maladaptive (Russo et al., 2012). Our data also have not included the assessment of participants' chronic stress, which has been closely associated with ACEs (Colman et al., 2016). Future studies should replicate the impact of early-life stress on WM task performance under induced negative arousal with consideration of chronic stress.

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The functional relevance of these findings should be further elaborated by relating these experimental effects to different development outcomes (Evans & Cassells, 2014).

Conclusion

This study provides evidence for the effect of induced negative arousal on WM consolidation speed but not storage capacity. This arousal effect on WM formation is modulated by the effectiveness of arousal induction and participants' early-life stress. These observations remain robust after taking into account additional individual differences variables, such as mood states and gender. By bridging these experimental and individual differences effects, our findings illustrate the conditions under which emotion contexts can influence WM, facilitating our understanding of the complex relationships between emotion and cognition.

Author Note

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Figure Legends

Figure 1. Possible effects of induced medium-level negative arousal on WM task performance over time. Negative arousal may speed up WM consolidation without affecting WM storage capacity, allowing more items encoded into WM but only within the initial WM consolidation time window (A). It could also boost the overall WM task performance, leading to more encoded items across time until a boosted (B) or fixed (C) capacity limit is reached. It is also possible that induced negative arousal boosts both WM consolidation speed and storage capacity (D). Together, these reflect the factorial combination of the potential experimental effects on WM consolidation speed and storage capacity (see similar predictions in Ngiam et al., 2018; Xie & Zhang, 2017b).

Figure 2. Change detection task following emotion induction using stimuli from the International Affective Digital Sounds (IADS). On each trial of the task, a 6-second sound clip from the IADS stimulus set was presented following a fixation display of 200 ms after a jittered 800-ms intertrial interval (ITI). During the first 5 seconds of the sound, there was no stimulus on the screen except for the fixation circle. During the last 1,000 ms of the sound, a memory array, a mask array, and a test array were sequentially presented on the screen. Participants reported if the presented color in the test array was new or old as compared with the color at the same location in the memory array. Following the change detection response, participants used the Self-Assessment Manikin (SAM) 9-point scales to report the arousal and valence of the IADS sound presented at the beginning of the trial.

Figure 3. Negative IADS sounds induce negative arousal. (A). Average standardized pupil size in the negative and neutral conditions over time. Error bars represent standard errors of the pupil size measures. (B) During the measurement window from 2000 ms to 4000 ms after sound onset, participants' pupil sizes were significantly greater in the negative relative to the neutral condition. (C) Negative IADS sounds were also rated as being more negative and more arousing as compared with neutral sounds. (D) The association between the objective (pupil size) and subjective (rating) aspects of induced negative arousal were strong across emotion conditions based on repeated-measures correlation. ****, $p < .0001$.

Figure 4. WM task performance under induced negative arousal. (A) Participants tend to remember more WM items as the amount of time allowed for WM consolidation increases. Furthermore, they tend to encode more WM items in the long SOA condition under negative arousal relative to the neutral condition. (B) This observation manifests at the group level across participants, as indicated by a greater ratio of encoded WM items in the long SOA condition on average under induced negative arousal, as compared with the lower and upper bounds in WM performance set by the short SOA and no-mask conditions. (C) Based on a permutation test by shuffling the emotion condition labels 10,000 times while retaining the SOA condition labels, we obtain significance evidence supporting the difference in WM consolidation speed between the emotion conditions in (B). Error bars and shaded area represent bootstrap standard errors across participants. *, $p < .05$.

Figure 5. The effect of induced negative arousal on WM consolidation speed is modulated by the effectiveness of arousal induction. (A) The distribution of windowed pupil size measure across participants suggests that arousal induction was ineffective in a subset of participants, evidenced by the below-0 pupil size differences between negative and neutral conditions. (B) Participants in the effective arousal induction group show a significant impact of induced negative arousal on WM consolidation speed (C), whereas participants in the ineffective arousal induction group show modest experimental effects (D, E). (F) The difference in the corrected WM consolidation effect was significantly higher in the effective group relative to the ineffective group. Error bars and shaded area represent bootstrap standard errors across participants. ***. $p < .01$.

Figure 6. Relationships between the objective measure of induced negative arousal and WM effects assessed based on canonical (A, C) and repeated-measure correlations (B, D). (A) Relationship between induced negative arousal measured by pupil size between 2-4 s after IADS sound onset (negative – neutral) and the arousal effect on WM consolidation speed (negative – neutral). (B) Repeated-measure correlation of induced arousal measured by pupil size and WM consolidation speed without taking the difference score between negative and neutral conditions. (C) Relationship between induced negative arousal measured by pupil size between 2-4 s after sound onset (negative – neutral) and the arousal effect on WM capacity estimate in the no-mask condition (negative – neutral). (D) Repeated-measure correlation of induced arousal measured by pupil size and WM capacity without taking the difference score between negative and neutral conditions. In these figures, the dots represent data from each participant (color coded in B, D for different subjects), the solid lines presentation linear fits of the data between subjects (A, C) or within subject (B, D). The dashed lines reflect the 95% confidence interval of the fit in A and C.

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Supplementary Online Materials

Reliability of windowed pupil size measure in the current sample

We conducted a reliability analysis on pupil size measures based on splitting the trial-level data into random halves over 1000 iterations. We took the average correlation of windowed pupil size measures between these random halves across participants as the representative split-half reliability for pupil dilation measures. An example of this analysis is shown in Supplementary Figure S1, separately for the negative and neutral conditions. In our current sample, we found that there was high split-half reliability (mean $r = 0.83$) for the windowed pupil size measure in both the negative and neutral conditions.

Supplementary Figure S1. Assessing split-half reliability of windowed pupil size measure in the current sample. This plot shows the example data from one iteration of the split-half analysis. We have repeated this analysis 1000 times. Here, in this example, each dot represents a participant's windowed pupil size measure in two random halves of the data within the participant. The thick line represents the diagonal ($r = 1$) and the thin line represents the linear fit of the data. Across participants, there is high split-half reliability, with a mean $r = 0.83$ across 1000 iterations, for both the negative and neutral conditions.

Characterizing individual differences with mixed-effect regression

As a complementary analysis to ANCOVA, we also performed mixed-effect regression. We first defined the outcome variables as WM consolidation speed (difference in Cowan's K between short and long SOA conditions) and WM storage capacity (Cowan's K in the no-masking consolidation). Next, we modeled these outcome variables a function of the various predictors, including emotion condition (negative vs. neutral), the effectiveness of induced negative arousal (effective vs. ineffective), early-life stress level (more vs. less ACEs), depressed mood (PHQ score), anxious feeling (GAD score), and gender. Among these predictors, emotion condition was a within-subject factor, whereas others were between-subject factors. The correlation matrix of these variables is summarized in Supplementarily Table S2.

Similar to ANCOVA, our goal is to test whether the moderation effect of the effectiveness of induced negative arousal (effective vs. ineffective) and early-life stress (ACEs score) remain robust after taking into account other covariates. Hence, in the baseline model, we first entered emotion condition, depressed mood, anxious feeling, gender, effectiveness of induced negative arousal, and early-life stress as predictors (Model 1). Next, we added the interaction effect between emotion condition and the effectiveness of induced negative arousal (Model 2) and then the interaction effect between emotion condition and early-life stress level (Model 3). Finally, we evaluated the full model that includes the three-way interaction among emotion condition, effectiveness of induced negative arousal, and early-life stress level (Model 4). With this hierarchical method, we entered the variable of interest to a model at last, such that its contribution to the outcome variable could not be accounted for by other variables that have already been considered. We compared R^2 and AIC to evaluate whether adding this additional variable can provide a significantly better fit to the data.

As summarized in Table S3, we found that the observed Cowan's K between long and short SOA conditions, namely the estimated consolidation speed, was significantly predicted by Emotion condition and gender when no interaction effect was considered (Model 1). However, depressed mood and anxious feelings did not significantly influence WM task performance. Adding the interaction effect between emotion condition and the effectiveness of arousal induction ($\beta = -.16, p = .0065$, Model 2) significantly improved model fit (Model 2 vs. 1: difference in $R^2 = 0.05$, difference in AIC = -5.28 , $\chi^2(1) = 7.29, p = .0069$). This interaction effect therefore could not be accounted for by individual differences in gender, early-life stress level, depressed mood, or anxious feelings. When the interaction between emotion condition and early-life stress level was included, the model fit was further improved (Model 3 vs. 2: difference in $R^2 = 0.06$, difference in AIC = -8.20 , $\chi^2(1) = 10.20, p = .0014$). This was because early-life stress level significantly moderated the emotional effect on WM consolidation speed ($\beta = -.18, p = .0012$). This moderation effect could not be accounted for by other variables that have already been considered in Model 2. Finally, when the three-way interaction was included and emotion condition, effectiveness of induced negative arousal, and early-life stress level were added (Model 4), there was not significant improvement in model fit (Model 3 vs. 4: difference in $R^2 = 0.01$, difference in AIC = 3.39 , $\chi^2(2) = 0.61, p = .74$). These results suggest that both the effectiveness of arousal induction and participants' early-life stress level captured by ACEs can significantly and potentially independently moderate the experimental effect of induced negative arousal on WM consolidation speed.

Does induced negative arousal interact with item-level differences of the memory stimuli?

We conducted an item-level analysis to check if certain colors would lead to a greater emotion effect on WM task performance. We obtained no significant evidence for this alternative account. First, in the current experiment, memory colors were randomly sampled from 180 possible colors in a circular color space (without replacement within a given trial), instead of a few fixed categorical colors. This wide range of memory feature space has reduced the contribution of potential memory biases of certain items on the overall task performance. Second, we evaluated the memorability of colors across subjects (Xie, Bainbridge, Inati, Baker, & Zaghoul, 2020). Memorability is calculated by how likely a target color would lead to a correct memory response among participants, namely $p(\text{memorability}) = \# \text{subj tested correct using this color} / \# \text{sub tested using this color}$. We found limited evidence for the interaction between emotion and color memorability (see Supplementary Figure S2). While this could be due to noisy estimates of color memorability for the 180 colors, smoothing the data across the color space (e.g., grouping all the red hues together) had not revealed a significant emotion effect either. These data, therefore, suggest that the main experiment findings on WM may not be attributed to the interaction between arousal and item-level differences of the memory stimuli (e.g., salience).

Supplementary Figure S2. WM accuracy across colors and emotion conditions. In this figure, WM accuracy is measured at the item level, which equals $\# \text{subj tested correct using this color} / \# \text{sub tested using this color}$.

Individual Differences in Self-report Arousal Responses on Experimental Outcomes

In parallel to Figure 6, we have also examined whether self-report arousal measures can account for the significant amount of within- and between-subject variance in experimental outcomes explained by pupil size measures. We found that although self-report measures could account for a significant amount of within-subject variance in experiment outcomes (Supplementary Figure S3B), self-report arousal ratings were not sufficient to capture individual (between-subject) variation in experiment outcomes related to WM consolidation speed estimate (Supplementary Figure S3A).

Supplementary Figure S3. Relationships between the self-report arousal and WM effects assessed based on canonical (A, C) and repeated-measure correlations (B, D). In these figures, the dots represent data from each participant (color coded in B, D for different subjects), the solid lines presentation linear fits of the data between subjects (A, C) or within subject (B, D). The dashed lines reflect the 95% confidence interval of the fit in A and C.

Individual Differences in ACEs and Experimental Outcomes

In our current data, we found that the total score of ACEs did not significantly modulate emotional responses related to the sounds assessed either using subjective report or pupil size (F 's < 1 ; see Supplementary Table S4 for details). These results appear to be consistent with prior observations that the effectiveness of arousal induction at a given moment and early-life stress are separable from one another (e.g., Pieritz, Rief, & Euteneuer, 2015). Yet, this does not preclude the possibility that certain types of ACEs were correlated with the effectiveness of induced arousal. For example, individuals with childhood sexual contact abuse experiences were more sensitive to negative relative to neutral IADS sounds ($r = .26$ [.08, .42], $p = .005$; $\rho = .27$ [.09, .43], $p = .003$; Kendall's $\tau = .22$ [.10, .33], $p = .003$; remain statistically significant after Bonferroni correction; see Supplementary Table S5).

Furthermore, ACEs and the effectiveness of arousal induction may have an aggregated impact on experimental outcomes. To further visualize these individual differences in experimental outcomes, we plotted each individual participant's experimental effect size (i.e., the difference in consolidation speed estimate between negative and neutral conditions) in Supplementary Figure S5. We found high ACEs participants with more effective arousal induction (red solid triangles) showed the most robust experiment effect in the predicted direction (mostly above 0) as compared with participants in other groups. By contrast, low ACEs participants with ineffective arousal induction (blue dots) showed the least experiment effect (mostly below 0). This observation is supported by a significant difference in the experimental effect between these groups of participants ($t_{(36)} = 4.06$, $p = .00025$, Cohen's $d = 1.32$ [0.63, 2.53]). By resampling participants' data with replacement over 5000 iterations (bootstrapping) based on the same effect size metric of Cohen's d , we found that the absolute magnitude of this combined effect was significantly higher and was almost twice the size as compared with that when only the main effect ACEs (Cohen's $d = 0.63$ [0.18, 1.07]) or arousal induction effectiveness (Cohen's $d = 0.56$ [0.15, 0.97]) was considered (bootstrapped $ps < 0.001$). These results suggest that individual differences may exert an aggregated impact on the current experimental outcomes. Furthermore, data from Supplementary Figure S5 also suggest that the significant modulation of arousal induction effectiveness on the experimental outcomes is significant regardless of whether participants were in the high ($F_{(1, 23)} = 5.14$, $p = .033$, $\eta^2_p = .183$) or low ($F_{(1, 93)} = 5.51$, $p = .021$, $\eta^2_p = .056$) ACE groups. This result thus suggests that the experimental effects manifest across individuals when the experimental induction of arousal is effective.

Yet, as mentioned in the main text, the current data are limited by a smaller sample size with these split-group analyses, and hence have a small statistical power to detect these effects. These exploratory findings therefore would require further replication with independent estimates of these effect sizes based on a different participant cohort and in a larger sample of participants with ACEs.

Supplementary Figure S4. The effect of induced negative arousal on WM consolidation speed is modulated by participants' early-life stress captured by ACEs. (A) The distribution of ACEs in the current sample reveals a significantly higher percentage of participants who have reported high ACEs (≥ 4) as compared with a population-based norm in previous study (Anda et al., 2006). (B) Participants with more ACEs show a significant impact of induced negative arousal on WM consolidation speed (C), whereas participants with less ACEs show modest experimental effects (D, E). (F) The difference in the corrected WM consolidation effect is significantly higher in individuals with more ACEs relative to those with less ACEs. Error bars and shaded area represent bootstrap standard errors across participants. **, $p < .01$.

Supplementary Figure S5. The individual effect of induced negative arousal on WM consolidation speed sorted by effect size. Within each participant, the experiment effect is defined as the difference in consolidation speed estimation between the negative and neutral conditions. We mark everyone's designation in the 2 (arousal induction effectiveness) and 2 (ACE group) between-subject factorial design based on different symbols. Solid red triangles represent individuals with more ACEs and effective arousal induction; hollow red triangles represent individuals with more ACEs and ineffective arousal induction; grey dots individuals with fewer ACEs and effective arousal induction; and blue dots individuals with fewer ACEs and ineffective arousal induction. The overall effect size across participants (random effect) along with its standard error (SE) is marked as a green bar on the right side of the plot, whereas the group means and SEs marked by different colors are summarized on the left side of the plot. *. $p < .05$; *n.s.* = not significant.

Supplementary Table S1. IADS Indices for the Chosen Stimuli

Sound Index	Negative-Medium	Neutral
1	289	375
2	261	370
3	116	377
4	105	132
5	106	374
6	291	171
7	380	705
8	502	170
9	244	262
10	710	698
11	730	368
12	423	373
13	133	322
14	283	701
15	910	376
16	699	720
17	319	246
18	296	627
19	241	728
20	295	700
21	729	723
22	293	358
23	280	708
24	626	382
Valence from the norm		
Mean	3.29	5.10
SD	0.54	0.49
IQR (1 st ,3 rd)	(3.04, 3.66)	(4.80, 5.41)
Arousal from the norm		
Mean	6.18	4.33
SD	0.30	0.47
IQR (1 st ,3 rd)	(6.08, 6.36)	(4.14,4.65)

Note: IQR = Inter-quantile range. For normative ratings, they arrange from 1 to 9. For valence, smaller numbers indicate more negative emotional values, whereas larger numbers indicate more positive emotional values. For arousal, the larger number it is, the more emotionally intensive it is for the sound.

Supplementary Table S2. Mix-effect Regression Analyses for WM Consolidation Speed

	Model1		Model2		Model3		Model4	
	β	Z	β	Z	β	Z	β	Z
1. Emotion ^a	-0.13*	2.21	-0.13*	2.27	-0.13*	2.36	-0.13*	2.36
2. Gender ^b	-0.15*	2.20	-0.15*	2.20	-0.15*	2.20	-0.15*	2.18
3. Depressed mood (PHQ)	0.04	0.39	0.04	0.39	0.04	0.39	0.04	0.38
4. Anxious feeling (GAD)	0.05	0.51	0.05	0.51	0.05	0.51	0.05	0.50
5. Early-life stress level (ACEs) ^c	0.02	0.21	0.02	0.21	0.02	0.21	0.02	0.21
6. Arousal induction effectiveness ^d	0.06	0.93	0.06	0.93	0.06	0.93	0.06	0.93
7. Interaction, emotion:arousal			-0.16**	2.72	-0.18**	3.16	-0.18**	3.15
8. Interaction, emotion:ACEs					-0.18**	3.22	-0.19**	3.22
9. Interaction, arousal:ACEs							-0.01	0.15
10. Interaction, emotion:arousal: ACEs							-0.04	0.75
R²	0.14		0.19		0.25		0.26	
AIC	683.60		678.31		670.11		673.50	
Model comparison			Model 2 vs. 1: $\chi^2_{(1)} = 7.29$, $p = .0069$		Model 3 vs. 2: $\chi^2_{(1)} = 10.20$, $p = .0014$		Model 4 vs. 3: $\chi^2_{(2)} = 0.61$, $p = .74$	

Note: a) Emotion condition. Negative is coded as 1 and neutral is coded as 2; b) Male is coded as 1 and female as 0; c) Early-life stress level is defined based on the cut-off score of 4 based on the norm (Anda et al., 2006). High ACE group is coded as 1, reflecting more early-life stress; and low ACE group is coded as 0, reflecting less early-life stress. d) Arousal induction effectiveness is defined by objective measure of pupil size difference between negative and neutral conditions prior to the working memory task. Participants who had larger pupil sizes under negative sounds relative to neutral sounds were coded as 1, reflecting more effective arousal induction; whereas participants who showed the opposite pattern were coded as 0, reflecting less effective arousal induction. All the variables were standardized before performing the regression analysis. Significance level is assessed by Wald's Z test. *. $p < .05$; **. $p < .01$.

Supplementary Table S3. Pair-wise Correlations of Variables of Interests in the Current Study

	1	2	3	4	5	6	7	8
1. WM consolidation speed estimate ^a (negative – neutral)	—							
2. WM capacity estimate ^b (negative – neutral)	-.16	—						
3. Gender	-.05	.03	—					
4. Depressed mood (PHQ)	.05	.08	-.06	—				
5. Anxious feeling (GAD)	-.0002	.05	-.15	.73***	—			
6. Early-life stress (ACEs) ^c	.24**	.03	.03	.40***	.21*	—		
7. Early-life stress level (ACEs≥4)	.25**	.01	-.10	.55***	.33***	.74***	—	
8. Pupil size (2-4s, negative – neutral)	.24**	-.07	-.08	-.09	-.18*	.04	-.01	—
9. Arousal induction effectiveness (mean pupil size negative > neutral)	.24**	-.05	-.01	-.11	-.10	-.10	-.11	.73***

Note: a) WM consolidation speed estimate is calculated as the difference in Cowan's K between long and short SOA conditions. b) WM capacity estimate is calculated as the Cowan's K in the no-mask condition. c) ACEs total score. Pearson or point-biserial correlations are reported in the table. *. $p < .05$; **. $p < .01$; ***. $p < .001$.

Supplementary Table S4. Overall (total score) ACEs and Emotional Response Measures

	Windowed Pupil Size			Arousal Rating			Valence Rating		
	$F(1, 102)$	p	η^2_p	$F(1, 102)$	p	η^2_p	$F(1, 102)$	p	η^2_p
Within-subject/Mixed effects									
Emotion ^a	26.64	<.001	0.21	108.94	<.001	0.52	181.1	<.001	0.64
Emotion:ACEs	0.002	0.97	<0.001	0.31	0.58	0.003	0.36	0.55	0.004
Between-subject effects									
ACEs	0.61	0.44	0.006	0.081	0.78	0.001	0.93	0.34	0.009

Note: a). Emotion condition.

Supplementary Table S5. Correlations Among Different Sub-component of ACEs and Arousal Sensitivity Measure (i.e., Windowed Pupil Size Difference Between Emotion Conditions).

ACE Sub-components	<i>Pearson's</i> <i>r</i>	95% Confidence Interval	<i>p</i> _{<i>Pearson</i>}	<i>Spearman's</i> ρ	95% Confidence Interval	<i>p</i> _{<i>Spearman</i>}	Kendall's τ	95% Credible Interval	<i>p</i> _{<i>Kendall</i>}
1. Emotion Abuse	-.004	[-.18, .18]	.97	-.04	[-.22, .14]	.64	-.04	[-.16, .08]	.57
2. Physical Abuse	.08	[-.01, .26]	.38	.02	[-.16, .20]	.83	.01	[-.11, .13]	.88
3. Sexual Contact Abuse	.26**	[.08, .42]	.005^a	.27**	[.09, .43]	.003^a	.22**	[.10, .33]	.003^a
4. Exposure to Alcohol or Other Substance Abuse	-.09	[-.26, .10]	.35	-.11	[-.29, .06]	.20	-.09	[-.21, .03]	.21
5. Mental Illness	.111	[-.07, .28]	.23	.11	[-.08, .28]	.25	.08	[-.04, .20]	.25
6. Violent Treatment of Mother or Stepmother	.099	[-.08, .27]	.28	.06	[-.12, .24]	.51	.05	[-.07, .17]	.48
7. Criminal Behavior in the Household	-.06	[-.24, .12]	.53	-.04	[-.22, .14]	.67	-.03	[-.15, .09]	.67
8. Parental Separation or Divorce	-.001	[-.19, .17]	.93	-.06	[-.23, .12]	.54	-.05	[-.16, .07]	.54

Note: a. Bonferroni corrected *p* value is .035, .024, and .024. respectively. **. *p* < .01.