Preliminary and incomplete

Long-term impacts on memory function of exposure to a natural disaster

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Abstract:

We investigate the impact on memory function of exposure to a large-scale, unanticipated natural disaster, the 2004 Indian Ocean tsunami, focusing on adults age 45y and older at the time of measurement, which is almost two decades post-tsunami. Data are drawn from the 19-year follow up of the Study of Tsunami Aftermath and Recovery, a population-representative longitudinal study with a population-representative baseline conducted 10 months before the tsunami. Comparisons are drawn using several different memory measurements including widely-used word-, story-, and picture-based assessments as well as a recently-developed protocol founded in neuroscience that measures olfactory-related memory adjusting for olfactory function. We leverage plausibly exogenous variation in exposure to the stresses of the tsunami, which killed over 5% of the population, and document that olfactory-related memory is significantly worse among the exposed indicating adverse effects of tsunami exposure on memory nearly 20 years later. The word- and picture-based measures do not vary with exposure. Additional analyses indicate the word- and picture-based measures of memory are related to measures of olfactory function all of which vary significantly with education. In contrast, the olfactory memory that adjusts for olfactory function is not related to education.

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1. Introduction

Population aging around the globe has made understanding the causes and consequences of memory loss an essential scientific question. Measuring memory is not straightforward. Measurement challenges are particularly acute in contexts where literacy and numeracy are low since most measures are designed for literate and numerate populations. Drawing comparisons between cohorts or populations that have different levels of education is difficult. We investigate the performance of an innovative method for assessing memory function that is grounded in olfactory neuroscience and does not require literacy or numeracy, so that the measure is unlikely to reflect both variation in memory and variation in education. We draw comparisons between the olfactory-based measures and widely-used word- and picture-based assessments including those used in the Harmonized Cognitive Assessment Protocol (HCAP). We examine these measures of memory for a population-representative sample of adults age 45y and older at the time of assessment in 2024, drawing contrasts between those who were directly exposed to the stresses of the 2004 Indian Ocean tsunami with comparable adults who were not directly exposed. These contrasts can be interpreted as providing causal evidence on the long-term impacts of stressor exposure on memory function.

While findings from laboratory studies and animal models show mechanistic support linking stress, the HPA-axis, hippocampal function and, therefore, memory function, testing these hypotheses in human populations is challenging (Miller and O'Callaghan 2005). Although epidemiological studies generally find adverse relationships between stress and stressful events earlier in life with dementia or memory later in life, it is not clear that these relationships are causal (Franks et al. 2021; Luo, Beam, and Gatz 2023; Wang et al. 2012).

The Study of Tsunami Aftermath and Recovery (STAR) provides unique opportunities to identify the causal effect of large-scale stressors on memory in later life. Specifically, STAR is designed to directly address several key challenges that arise when interpreting evidence on long-term health outcomes in the aftermath of stressful exposure (Aristizabal et al. 2020). First, exposure to adverse events typically depends on individual, family and environmental characteristics that are hard to measure and confound analyses. Second, few studies draw comparisons between individuals who are plausibly comparable apart from exposure to the adverse event. Third, studies of long-term effects of exposure usually rely on recalling events years before, the accuracy of which is unclear especially as the interval from the event lengthens. This research leverages effectively random exposure to an unanticipated, major stressor, the 2004 Indian Ocean tsunami. Using population-representative longitudinal data from STAR collected from respondents who were living along the coast of Aceh, Indonesia, at the time of the tsunami, we compare those who were living in communities that were directly affected by the tsunami waves with people living in nearby, comparable communities that were spared. Since the tsunami was completely unanticipated and where it made landfall depended on a complex function of the location in the Indian Ocean of the earthquake, the sea-floor topography and idiosyncratic feature of the coastline, it is plausible to treat this community-level measure of tsunami exposure as exogenous. (Frankenberg et al. 2011). This community-level measure of exposure is complemented with an individual-specific measure of being caught up in the tsunami waves. Using this second measure of exposure, we draw comparisons between people who were living in the same coastal community at the time of the tsunami.

Using STAR data, we have shown that exposure to the 2004 tsunami leaves a long-lasting imprint on health and wellbeing. "Scarring" effects of the tsunami raise long-term mortality for vulnerable individuals, despite positive mortality selection at the time of the tsunami (Frankenberg et al. 2011; Frankenberg, Sumantri, and Thomas 2020). Using tablet-based games, we have shown that exposed individuals present with deficits in declarative memory (Sheridan et al. 2024). There is evidence of HPA-axis burnout 14 years after exposure, particularly for females who presented with sustained, elevated post-traumatic symptoms (Lawton et al. 2023). This is particularly salient, as experimental evidence implicates lifespan HPA-axis distortions in later-life memory loss (Lupien et al. 2005; Sapolsky, Krey, and McEwen 2002).

As the population has continued to age, long-term longitudinal follow-up has enabled focused assessment on the role of exposure to the 2004 tsunami on cognition and memory among individuals exposed earlier in life. However, since word- and picture-based assessments of memory potentially measure variation in memory as well as variation in literacy, numeracy and education, we also use a novel olfactory-based approach to assessing memory that takes into account olfactory function. The olfactory system presents physiological and practical advantages for assessment of memory. The neural circuit of the olfactory system incorporates the hippocampus, central for memory, and is the most direct path between the hippocampus and external environment. Further, the entorhinal cortex is among the first areas to show Alzheimer's neuropathology (Murphy 2019). Scent assessment, particularly of odor memory, does not rely on numeracy or literacy and is less likely to be related to skills acquired in formal education or via labor force participation (Albers et al. 2016). Measuring olfactory memory is thus promising as a means to assess early signs of AD, as well as abstract away from measurement challenges related to education in particular. However, direct assessment of olfactory memory is complicated by wide variation in individual olfactory function, as well as variation in exposure to odors and learned associations (Poncelet et al. 2010). The three-stage design of the Percepts of Odor Episodic Memory (POEM) assessment addresses this, with two measures of olfactory function and one measure of olfactory memory. Taken together, the index produces a measure of olfactory memory that is conditional on olfactory function, which significantly improves the value of olfactory assessment (Albers et al. 2016). We field the POEM alongside more traditional word, story, and drawing-based recall assessments and draw comparisons between the outcomes.

While epidemiological findings outside the laboratory and clinic are not always consistent, they generally suggest negative or null effects of long-term stressors on memory (Franks et al. 2021; Luo et al. 2023; Wang et al. 2012). Findings from individuals with PTSD have found impaired memory at older ages, and self-reported adverse childhood experiences were generally linked with null-to-adverse impacts on memory function and decline depending on the specific experience (Golier et al. 2006; O'Shea et al. 2021). Self-reported stress in childhood and adulthood has been linked to dementia risk (Nabe-Nielsen et al. 2020; Radford et al. 2017). Following the 2011 earthquake in Japan, individuals over 65 at the time of the disaster who lost their homes (but not those who lost loved ones) were at higher risk of dementia onset (Hikichi et al. 2016; Shiba et al. 2021). We contribute to this literature by providing causal evidence on later-life memory changes among those exposed to a large-scale environmental stressor at much younger ages.

In doing so, we also provide evidence on the feasibility and utility of olfactory approaches to complement more traditional measures of memory in populations where word- and picture-based assessments are complicated by variation in educational attainment across cohorts. By drawing comparisons between olfactory-based memory assessment and word- and picture-based measures at scale, we shed further light on the socio-demographic relationships that affect interpretation in these contexts, and using exposure to the 2004 tsunami we show the potential value-add of olfactory measurement.

2. Data and Empirical Approach

2.A. Study of Tsunami Aftermath and Recovery

We present preliminary results from our study which is still in the field collecting data from survivors of the 2004 Indian Ocean Tsunami, 20 years after the tsunami. The Study of Tsunami Aftermath and Recovery (STAR) baseline consists of individuals who were living along the coast of Aceh and North Sumatra, Indonesia, in February and March 2004. Individuals were initially interviewed as part of SUSENAS, a national socio-economic survey of households which is population-representative at the kabupaten (district) level. All members of households included in the baseline and who were living in kabupaten along the coast of Aceh and the west of coast of North Sumatra are included in STAR (Frankenberg, Katz, et al. 2020; Frankenberg, Sumantri, and Thomas 2023). Over 5% of the baseline respondents died in the tsunami,

and every tsunami-survivor, including those who moved away from the baseline community, is eligible to be tracked in each STAR follow-up (Frankenberg et al. 2011). We have interviewed over 98% of the survivors in at least one post-tsunami follow-up and, in the most recent follow-up, completed in 2022, we re-interviewed over 93% of the surviving baseline respondents. Our current wave of data collection is an in-depth assessment on health and cognition of all respondents who were at the time of the tsunami living in one of a randomly selected 25% of the baseline STAR communities. All individuals aged 45 and older (approximately 25 and older at the time of the tsunami), are eligible for inclusion in the assessments of memory and cognition. We have completed about two-thirds of the target enumeration areas and we use data on 1,189 respondents who have assessed to date.[1], and expect to have over 1,600 individuals by the CAPRA-NBER conference date.

2.B. Exposure to the 2004 Indian Ocean Tsunami and empirical specification

On December 26, 2004, the Sumatra-Andaman earthquake struck shorelines throughout the Indian Ocean. The west coastline of Aceh, in Northwest Indonesia, was hardest hit, with waves up to 30m coming ashore within 15 minutes of the earthquake. Over 250,000 people along the coast of the Indian ocean were killed, and over half a million displaced in Indonesia alone.

The tsunami was entirely unexpected. Notably, unlike pacific-facing communities in Indonesia, which have relatively frequent exposure to tsunamis and as a result have warning buoys, the Aceh province had not seen a tsunami for over 600 years (Monecke et al. 2008). In the pre-tsunami baseline of STAR, over 90% of respondents said their home faced no natural disaster risk, and only 15 individuals said a tsunami was most likely to occur.

Exposure to the tsunami itself was dependent on an idiosyncratic function of wave direction, ocean floor and land topography, and their interaction. The Aceh province has many low-mountains that produce substantial local variation in the terrain (Degueldre et al. 2016; Frankenberg et al. 2011; Umitsu, Tanavud, and Patanakanog 2007). The resulting exposure was thus unable to be predicted *a priori* and highly variable – within a small geographic area, some communities were completely destroyed, while nearby communities were not.

Taking together the combination of the tsunami's unexpected nature with its highly variable and unpredictable impacts, we treat exposure to the stresses of the tsunami as plausibly exogenous with respect to future health and cognition.

We use several complementary measures of exposure to the tsunami. Our primary measure is based on the extent of destruction in a respondents' baseline community. Individuals are stratified into areas heavily damaged, or not heavily damaged, based upon information from satellite imagery before and after the tsunami, community informant reports, and interviewer observations after the tsunami occurred. This classification system has been cross-validated with community-specific mortality data, administrative and census data collected independently by statistics Indonesia (Frankenberg et al. 2011; Frankenberg, Katz, et al. 2020; Gray et al. 2014). Given the unanticipated and idiosyncratic nature of community exposure to the tsunami, we treat this first measure of tsunami exposure as exogenous.

Using this measure of exposure, we estimate the following empirical models. While we consider the community-level measure of exposure to be exogenous, potentially some coastal areas faced more risk than others, and may differ on some observable characteristics. We thus estimate models with kabupaten (district) fixed-effects, which absorb observed and unobserved characteristics of geography that are shared by communities within the kabupaten. Our estimates identify the effect of exposure to the tsunami based on

[1] All analyses will be updated when data collection has been completed, prior to the CAPRA-NBER conference.

baseline community within each kabupaten geography. For each cognitive outcome we evaluate M_i, we estimate the linear regression [1], where β_1 represents our coefficient of interest on our measure of baseline-community tsunami exposure T_C, X_i represents individual-specific covariates that may affect cognitive outcomes such as age, sex, and education, or in the case of our olfactory assessments whether they have had a recent cold or problem with olfaction. μ_K is a kabupaten fixed-effect, and ε is the error term.

$$M_i = \beta_0 + T_C \beta_1 + X_i\beta_2 + \mu_K + \varepsilon_i \qquad [1]$$

These analyses are complemented with an individual-specific measure that captures physical exposure to the tsunami. We use a dummy variable for whether or not an individual was directly swept away in the water. While of course related to the community-level measure, we abstract away from the potential influence of a community-level shock, and underscore the potential importance of being directly affected by the tsunami.

Empirically, these analyses complement the models introduced in [1]. Rather than use a community-level treatment and kabupaten fixed-effect, however, since these are individual-specific outcomes we examine them *within* each baseline community with a baseline community fixed-effects approach. As in [1], we consider the same outcomes and include individual-specific covariates, but now focus on individual-specific measures of exposure T_i, and include community fixed-effects δ_C.

$$M_i = \beta_0 + T_i \beta_1 + X_i\beta_2 + \delta_C + \varepsilon_i \qquad [2]$$

2.C. POEM assessment

The percepts of odor episodic memory (POEM) assessment is a novel approach grounded in olfactory neuroscience, that reaches beyond basic measures of olfactory function to additionally assess olfactory memory (Albers et al. 2016). Several key features of the POEM assessment make it well-suited to our context.

First, the olfactory system provides a unique window into memory function. The entorhinal cortex of the brain is among the first areas affected by neuropathological plaques and tangles that characterize Alzheimer's Disease (AD). Anatomically the olfactory bulb is the most direct path from the hippocampus to the external environment and an early site for AD and Lewy Body pathology (Albers et al. 2015; Murphy 2019; Ohm and Braak 1987). Olfaction, therefore, is likely a particularly sensitive system to harness in assessing memory, especially early preclinical signs of disease. In our relatively young population, this has the potential to pick up earlier traces of the tsunami's impact on brain health.

Second, relative to word-based methods, olfaction is less likely to be contaminated by literacy differences. While word-based assessments display substantial education gradients, particularly among those without formal education, olfactory-based memory assessment is non-verbal and POEM been shown to be minimally-linked to literacy, numeracy, and education (Albers et al. 2016; Banerjee et al. 2019).

While olfactory function has been linked to AD, use of olfaction to assess memory is limited by the fact that classic tests of olfaction do not directly assess memory, as well as the fact that olfactory function varies substantially from person to person, which may bias assessments (Adams et al. 2018; Albers et al. 2020). This is particularly a concern as olfactory function declines with age, potentially contaminating relationships with "memory" if olfactory function is not assessed earlier in life. The POEM assessment directly addresses these concerns, creating a 'sharpened' assessment of olfactory memory. It has been shown

to be a powerful predictor of AD and the future development of AD in cognitively normal adults (Albers et al. 2016, 2020; Ramirez-Gomez et al. 2022).

The POEM protocol has three stages: in the first stage, a panel of scents is introduced for respondents to identify via free recall, and then forced choice if needed. After some delay, respondents are presented with scents, one-half of which match the scents used in the first stage, whereas the other half are new. For each scent in this second panel, the respondent is asked whether or not they remember smelling it in the first panel; this provides a "memory score". In the third stage, the respondents are asked to smell pairs of scents. For some pairs the scents are the same, for others the two scents differ. For each pair respondents report whether the scents are the same or different, providing a measure of odor discrimination. The POEM score combines information from all three stages to construct an index that extracts that part of the "memory score" that is not explained by the capacity to identify or discriminate scents.

In order to calculate the POEM index, we operationalize the "POEM score" by regressing the score in the memory stage on performance in the identification and discrimination stages (Appendix table 1). The residual from this regression, the memory score conditional on identification and discrimination, is what we analyze as the POEM index.

After a year of carefully piloting the POEM protocol in our study area in Indonesia, we have developed a battery of scents that are culturally-appropriate and widely-recognized by the study population along with an efficient field protocol that uses 4 unique versions of the scents in the assessment, to assure no contamination when we assess multiple members of the same household.

2.D. Other outcomes

We draw comparisons between the POEM assessment as well as word, picture, and story-based measures of memory and ADRD that are used as part of the Harmonized Cognitive Assessment Protocol (HCAP) (Langa et al. 2020).

Specifically, we consider the difference between initial and delayed recall for a series of memory assessments: a subset of drawing-based recall measures from the constructional praxis assessment, 10-word list, and two story-based recall assessments (the Brave Man story, and another logical memory story) (Morris et al. 1989; Ryan et al. 2023).

For memory outcomes, we construct scores based not solely on the raw difference between initial and delayed recall, but rather on the percent recall difference – the proportion of the initial recall that is remembered after the delay. For example, if an individual remembered 8 words initially and 6 after a delay, they would have a -25% recall difference, rather than a raw difference of -2. We focus on this percent recall outcome in order to try and address ceiling effects that may be particularly binding in a low-education context. In appendix table 2, we examine the relationships between education and the raw versus the percentage scaled recall differences. Raw differences are negatively associated with education in our sample, while the percentage scaled differences is positively associated. This suggests ceiling effects may be particularly important – higher education individuals have larger absolute differences in initial versus delayed recall, but this appears to be attributable primarily to higher initial recall. When corrected, higher education individuals have improved recall performance.

In order to make all of the measures that we use comparable, we present results for all outcomes as z-scores, with mean 0 and standard deviation 1.

3. Results

3.A. Age, Sex, & Education

We begin by examining the relationships between our outcomes of interest with sex, age, and years of education. Coefficients from OLS regressions of a dummy variable for male sex, age in years, and years of education are shown in table 1. Regressions were estimated simultaneously, and include controls for smoking, congestion, exact time between presentation and recall, interviewer fixed effects, and survey version fixed effects. The first three columns of the table show the estimates of these relationships with each sub-component of the POEM assessment, and then the aggregate POEM score. On average, we find that males have lower performance on the olfactory identification component, but are not significantly different from females in the other components or in the POEM score. The differing performance in the first stage may potentially reflect differences in initial familiarity with the scents, many of which are spices or are food-related. Despite improved identification, recall does not appear to be significantly affected, though point-estimates are negative.

All three individual components of the POEM index are negatively related to age, however the POEM score is not significantly linked to age. This may reflect in part that the effects of aging on olfaction are conditioned out of the memory score when residualized on identification and discrimination. This finding is emphasized in Figure 1 – which plots the POEM sub-components as well as the combined POEM score with respect to age. All three sub-components are related to age in a similar fashion, but the combined POEM score is relatively flat.

All three sub-components of the POEM assessment are positively related to years of education. However, the relationships between the education and z-score of identification and discrimination are larger and more precise than for the memory stage. As a result, the POEM score itself is not significantly linked to education.

Turning to the memory assessments, only the percent recall difference from the constructional praxis assessment is related to sex, where males have a 0.14 standard deviation higher performance on average than females. All four memory assessments have negative point-estimates on the relationship between age and performance. Three of the four estimates are statistically significant, except for word recall with a t-statistic of -1.43. Non-parametric estimates of the relationship between age and z-score for each memory outcome show very similar relationships between age and memory, with the exception of the POEM index, which has a significantly flatter age profile than the other memory outcomes assessed (Figure 2).

All four of the memory measures that we consider show significant positive relationships between years of education and performance – with very similar point-estimates on the relationship between education and z-score. All point estimates are significant, and range between 0.019-0.03. As discussed above, these conclusions with regard to the relationship between education and memory performance differ significantly when using the unadjusted difference between immediate and delayed recall, suggesting a potentially important ceiling effect among individuals with higher education in this context.

3.B. Exposure to the 2004 Tsunami based on baseline community

We turn to examine the relationships between our outcomes of interest and measures of tsunami exposure in Table 2. Using our exogenous measure of heavy damage exposure based on community of residence at the time of the tsunami, we find that those exposed to the tsunami perform 0.2 standard deviations worse on the POEM index than those not heavily exposed. In the POEM sub-components, we do not find significant relationships with heavy tsunami exposure, though the point estimate on the memory score is similar to the POEM score, with a coefficient of 0.21 and a t-statistic of -1.61.

Most of the other word or picture-based measures of memory do not show significant relationships with tsunami exposure, with the exception of the logical memory story. Individuals heavily exposed to the tsunami perform 0.1 standard deviations better on the logical memory assessment.

One potential concern with interpreting these results is the potential impacts of mortality selection at the time of the tsunami. In order to assess whether mortality selection drives the exposure results that we see, we estimate an additional specification that restricts the sample to those at age 45-65 at the time of measurement. At the time of the tsunami, these individuals would have been approximately 26-46 years old. These individuals would have faced substantially lower mortality rates than individuals who are older in the sample (Frankenberg et al. 2011). We present parallel models restricted to age 45-65 in appendix table 3, and find very similar estimates to our primary specification – for example, the coefficient on the POEM index falls from -0.21 to -0.19, and remains statistically significant.

3.C. Individual-level exposures to the 2004 Tsunami

Models that leverage individual-specific exposures to the tsunami complement analyses based on our measures of baseline community exposure, which we consider exogenous. Estimates of the impact of individual exposure are constructed with community fixed-effects, and thus examine finer-grained exposures than we consider in our primary specification within communities that may or may not have been damaged.

We find significant relationships between being swept away in the water and the POEM index. Individuals swept away in the water perform 0.3 standard deviations worse on the POEM index than those who were not. Further, examining the POEM assessments sub-components show significant negative links between exposure and performance on the memory section, and at a 10% size of test suggest positive relationships between being swept in the water and olfactory identification performance.

Analyses find no relationship between these individual-specific measures of tsunami exposure and the HCAP-based word and picture recall assessments, with inconsistent directions of point-estimates across the measures.

3.D. Heterogeneity in exposure effects

In Table 3, we examine heterogeneity in the estimates of heavy damage exposure with respect to education, age, and sex. With respect to the POEM index, point estimates on the effect of heavy damage exposure are similar for those with lower and higher levels of education, though only reach statistical significance among those with higher levels of education. In contrast, estimates across education levels for other outcomes of interest are mixed or less precise. In the constructional praxis outcome, individuals with over 10 years of education had significantly better performance with heavy damage exposure, but individuals with lower education had a negative point estimate and a t-statistic of -1.62. In the other memory assessments, no statistically significant relationships with damage exposure were observed when stratified by education level.

Panel B examines heterogeneity by age. In the POEM index, effects are concentrated among those at older ages, with a significant and negative point estimate among those over 55. Among younger individuals, the point estimate is in the same direction but smaller, with a t-statistic of -1.59. These differences in the age trajectories are underscored in Figure 3, which shows diverging age trajectories for those heavily exposed vs non-heavily exposed. Among the other memory outcomes, no point estimates reach statistical significance, with the exception of the logical memory story, which shows a significant positive effect of damage exposure at a 10% size of test for those under 55.

Panel C assesses heterogeneity by sex. The POEM index estimates negative point estimates for both males and females, but the estimate for females is larger and statistically significant, while for males it is not. The other memory tests show inconsistent findings by sex. The constructional praxis assessment finds a significant positive effect of damage exposure for males, but a negative point estimate for women, and the

word recall test finds a significant negative effect on women at a 10% size of test, with a positive point estimate for men.

4. Discussion

This paper makes two contributions to the understanding of memory. First, we deploy the POEM test at scale in the Indonesian population, and draw comparisons with other word-, story-, or picture-based tools for assessing memory and risk of AD. In doing so, we underscore the challenges of measuring memory in a low-education context where education varies across cohorts, and present a new test for use in population studies that may provide additional value over typical recall tools for memory. Second, we provide substantive causal evidence on the role of stressful events on memory 20 years later, among individuals who were relatively young and cognitively healthy at the time of exposure. Examining heterogeneity in these effects further underscores the importance of and challenges with measurement.

Comparisons of the relationships between age, education, and sex across instruments underscore the challenges of measurement in our field context. Initial comparisons of word- and picture-based memory assessments that compare initial and delayed recall show important considerations of ceiling effects, and suggests using a percentage-scaled recall difference measure as we do in our analyses (Appendix table 2). Using these scaled recall differences, we find strong positive education gradients that are not present with the POEM index. To some extent, these may reflect real impacts of education on memory later in life. However, poor ability to complete these assessments among those without formal education in other contexts, such as India, suggest a potentially distorting role of formal education on these measures (Banerjee et al. 2019). Unlike with word or story recall, it is less likely that olfactory memory is linked to skills developed in formal education. Further, we find sex differences in performance in the constructional praxis assessment. While there are sex differences in the identification stage of the POEM assessment, these do not show up in the memory score or POEM index itself. These findings suggest a potentially useful role of the POEM assessment in population studies, where cross-cohort changes in education is a particular concern.

Laboratory and clinical neuroscience find mechanistic support linking stress, the HPA-axis, and memory, though testing these hypotheses at the population level is more challenging (Miller and O'Callaghan 2005). While epidemiological studies generally find adverse relationships between stress and stressful events earlier in life with dementia or memory later in life, it is difficult to interpret such relationships causally (Franks et al. 2021; Luo et al. 2023; Wang et al. 2012). Using a series of measures for tsunami exposure, including plausibly exogenous assessments of heavy tsunami exposure based on residence at the time of the tsunami, as well as individual-specific measures such as whether an individual got swept in the waves, or their PTSR score, we provide novel evidence on this question among individuals who would have been as young as 25 years old at the time of the tsunami. In particular, this study design complements prior work from STAR, which has documented HPA-axis 'burnout' linked to extended stress among those exposed to the tsunami (Lawton et al. 2023).

Using the POEM score, we consistently find adverse relationships between tsunami exposure and later life memory. Individuals heavily exposed based on their baseline community have -0.2 standard deviations worse performance on the POEM, and in models with community fixed-effects individuals who were swept away in the water have -0.3 standard deviations worse performance. We find no evidence for relationships between PTSR score and later life memory. In contrast, other measures of memory show inconsistent relationships with tsunami exposure. The only word or picture-based memory assessment to find any evidence of a significant effect is the logical memory story assessment, which finds a positive relationship with heavy damage exposure based on baseline community, and no effect of being swept away in the water. Other studies of the 2004 tsunami have found significant deficits in declarative memory among

the exposed but positive effects of tsunami exposure on individuals' executive function. We interpret the latter result as the effects of having to adapt to the new economic and social environment post-tsunami in mid-life (Sheridan et al. 2023).

These findings complement findings from the 2011 earthquake in Japan, which found 2.5-5 years later that risk of dementia was increased among adults over 65 at the time of exposure who lost their homes (Hikichi et al. 2016; Shiba et al. 2021). We find complementary evidence that exposure to stressful events earlier in life can have adverse consequences on memory nearly 20 years later.

Evaluating the heterogeneity in the tsunami's effects sheds further light on the differences across assessments. While the POEM score estimates consistent signs on the point-estimates by sub-group, effects are more precise among those with more education, older adults, and females. Figure 3 underscores the heterogeneity by age, showing smooth divergence in the age-POEM profiles among those who were and were not exposed to the tsunami. The concentrated impacts of the tsunami among women are consistent with other findings from STAR. We found the long-term effect of the tsunami on hair cortisol to be concentrated among women, with smaller but non-significant effects among men (Lawton et al. 2023).

While data collection for this project is ongoing, preliminary findings from the first 1,189 respondents underscore the challenges of measuring memory in low-education settings, and promising findings from a novel tool based on olfactory memory. Findings from the POEM assessment in particular provide new causal evidence suggesting adverse effects of exposure to the 2004 tsunami on memory emerging 20 years later.

Table 1: Relationships between memory markers (z-scored) and demographics
Respondents age 45+

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
					% Recall Difference:			
	Olf. Identification Score	Olf. Memory Score	Olf. Discrimination Score	POEM Score	Constructional Praxis	Brave Man Story	Logical Memory Story	Word Recall
(1) Male	-0.34	-0.124	-0.031	0.01	0.14	0.014	0.044	-0.081
	[-3.63]	[-1.18]	[-0.31]	[0.07]	[2.40]	[0.22]	[0.72]	[-1.16]
Age	-0.015	-0.01	-0.018	0.00	-0.01	-0.014	-0.013	-0.006
	[-4.56]	[-2.69]	[-5.03]	[-0.63]	[-2.44]	[-3.92]	[-3.34]	[-1.43]
Years of Education	0.046	0.025	0.037	0.01	0.02	0.019	0.027	0.03
	[7.22]	[3.60]	[5.34]	[1.27]	[2.71]	[2.28]	[3.80]	[3.76]

Notes: All outcomes z-scored with mean 0, standard deviation 1. Heteroskedasticity-robust t-statistics reported in brackets. OLS regression coefficients reported conditional on smoking, congestion, time between presentation and recall for each outcome, interviewer fixed effects, and survey version fixed effects. POEM score is calculated as the residual from a regression predicting olfactory memory score with olfactory identification and discrimination score.

Table 2: Effects of tsunami exposure on memory markers (z-scored)
Respondents age 45+

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
					% Recall Difference:			
	Olf. Identification Score	Olf. Memory Score	Olf. Discrimination Score	POEM Score	Constructional Praxis	Brave Man Story	Logical Memory Story	Word Recall
Panel A: Exposure based on pre-tsunami residence, district fixed-effects models.								
(1) Heavy Damage Exposure	0.008	-0.206	-0.07	-0.21	0.02	0.036	0.115	-0.01
	[0.05]	[-1.61]	[-1.07]	[-2.46]	[0.57]	[0.54]	[1.95]	[-0.11]
Panel B: Individual-specific tsunami exposures - swept away in water. Pre-tsunami community fixed-effects models.								
(1) Swept away in the water	0.169	-0.219	-0.034	-0.29	0.01	-0.05	0.058	0.076
	[1.67]	[-2.15]	[-0.35]	[-2.64]	[0.07]	[-0.56]	[0.39]	[0.60]

Notes: All outcomes z-scored with mean 0, standard deviation 1. T-statistics clustered at the district level reported in brackets. OLS regression coefficients reported conditional on gender, smoking, congestion, time between presentation and recall for each outcome, interviewer fixed effects, and survey version fixed effects.

Table 3: Age and education heterogeneity in tsunami effects

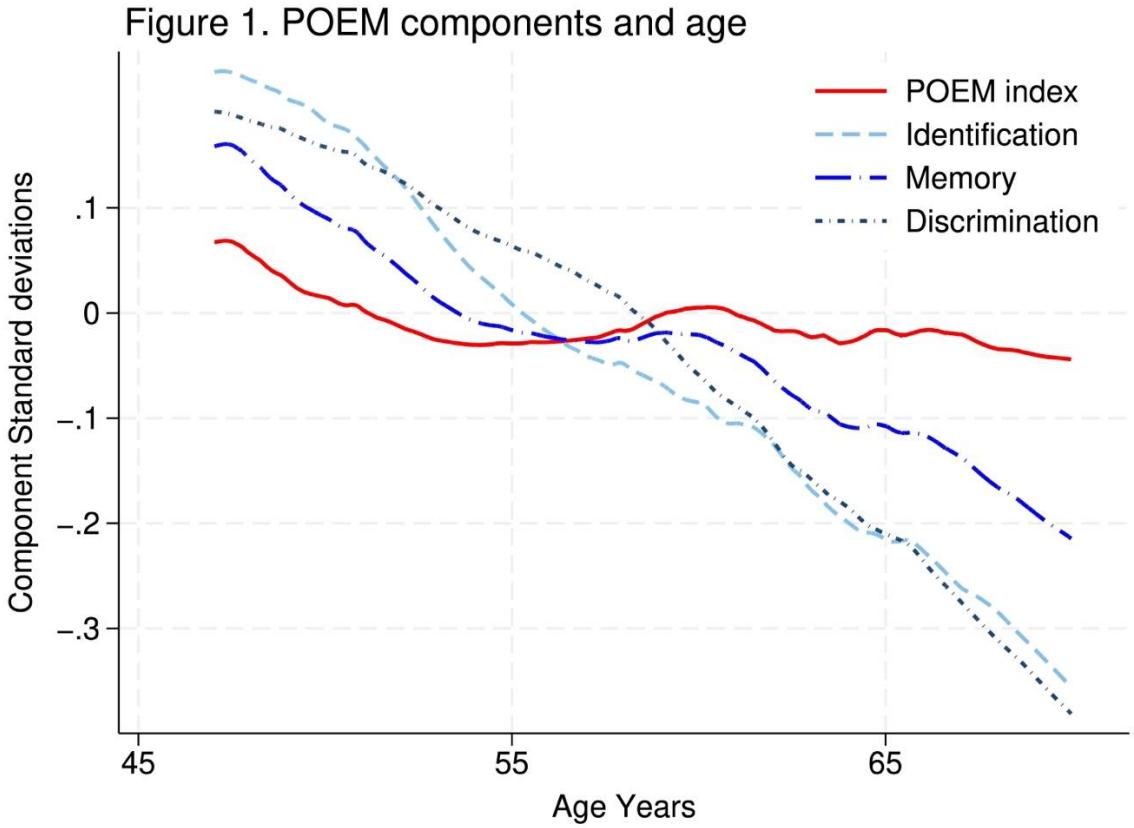
Respondents age 45+

Panel A: Education	[1]		[2]		[3]		[4]		[5]	
			% Recall Difference:							
	POEM Score		Constructional Praxis		Brave Man Story		Logical Memory Story		Word Recall	
Years of education:	Less than 10	10+	Less than 10	10+	Less than 10	10+	Less than 10	10+	Less than 10	10+
(1) Heavy Damage Exposure	-0.17	-0.24	-0.09	0.20	0.005	0.073	0.204	-0.004	0.056	0.014
	[-1.47]	[-2.03]	[-1.62]	[4.60]	[0.04]	[1.04]	[1.48]	[-0.07]	[0.41]	[0.24]

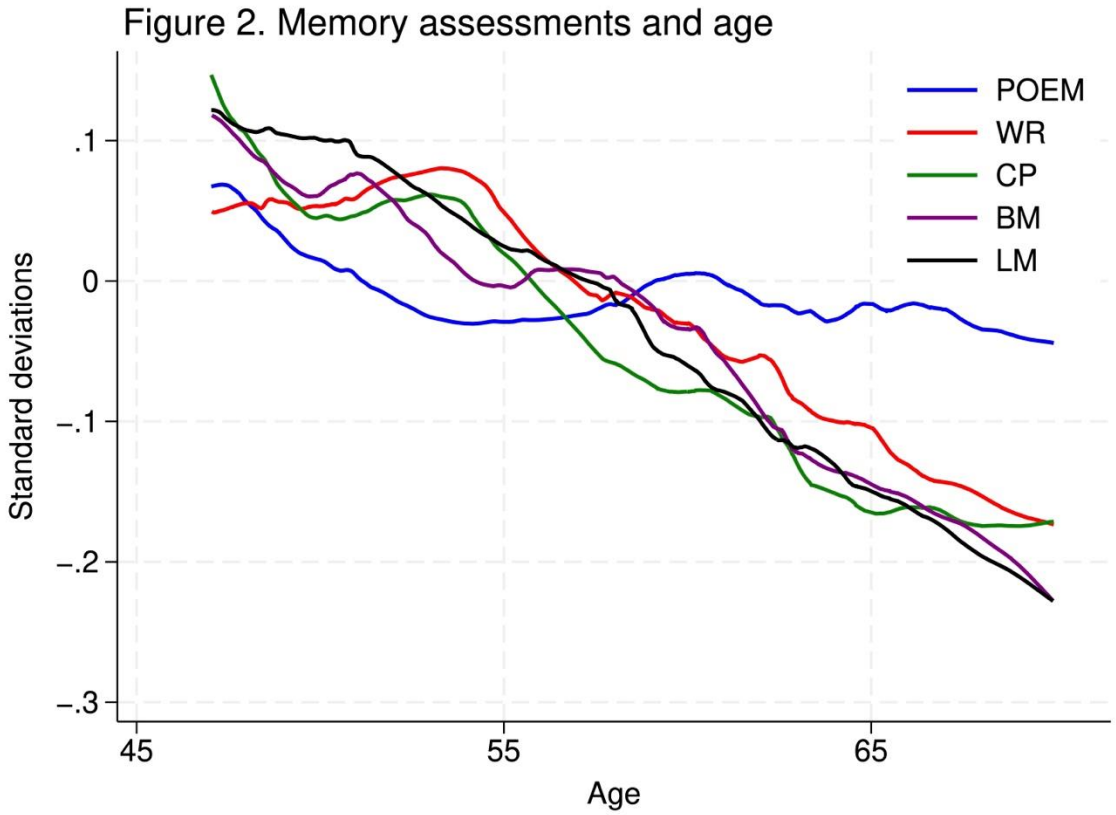
Panel B: Age	[1]		[2]		[3]		[4]		[5]	
			% Recall Difference:							
	POEM Score		Constructional Praxis		Brave Man Story		Logical Memory Story		Word Recall	
Respondent Age	Less than 55	55+	Less than 55	55+	Less than 55	55+	Less than 55	55+	Less than 55	55+
(1) Heavy Damage Exposure	-0.14	-0.28	0.04	0.00	0.127	-0.045	0.104	0.117	0.051	-0.104
	[-1.59]	[-3.38]	[0.49]	[0.04]	[1.37]	[-0.41]	[1.76]	[0.74]	[0.37]	[-0.78]

Panel C: Sex	[1]		[2]		[3]		[4]		[5]	
			% Recall Difference:							
	POEM Score		Constructional Praxis		Brave Man Story		Logical Memory Story		Word Recall	
Respondent Age	Females	Males	Females	Males	Females	Males	Females	Males	Females	Males
(1) Heavy Damage Exposure	-0.32	-0.09	-0.07	0.12	-0.077	0.151	0.031	0.173	-0.144	0.151
	[-3.27]	[-0.58]	[-0.58]	[2.68]	[-0.96]	[1.16]	[0.24]	[1.18]	[-1.67]	[0.94]

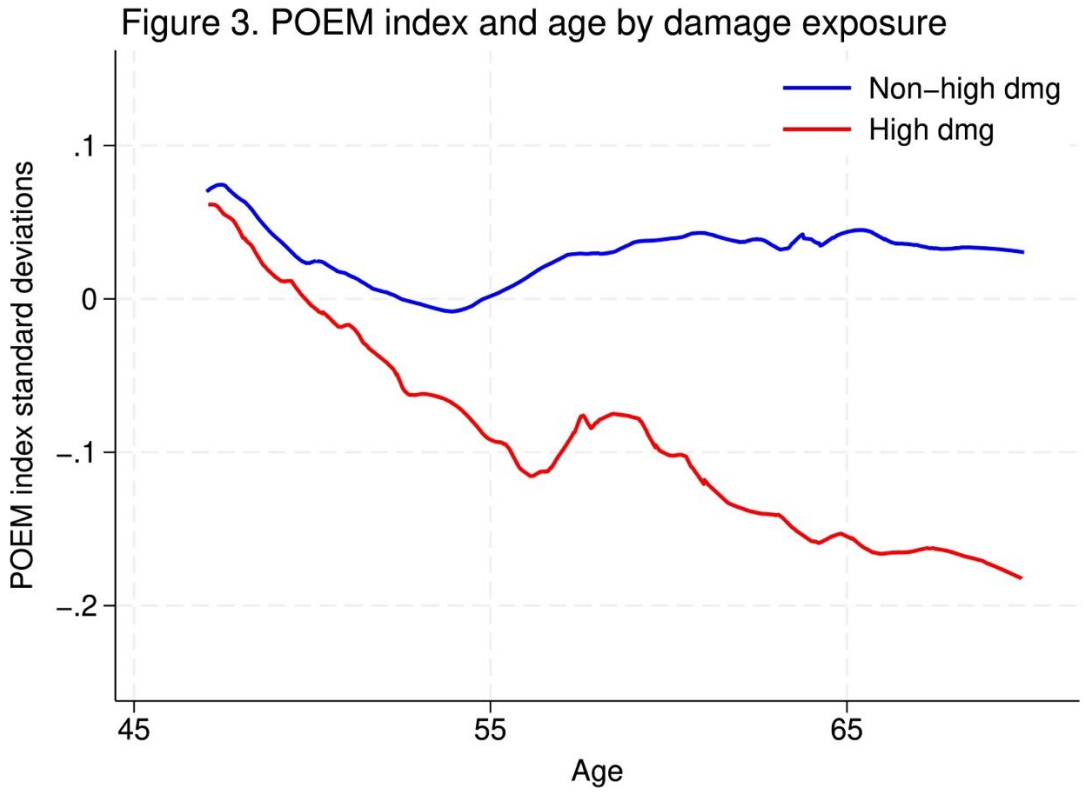
Notes: All outcomes z-scored with mean 0, standard deviation 1. All models include district fixed-effects. T-statistics clustered at the district level are reported in brackets. OLS regression coefficients reported conditional on gender, smoking, congestion, time between presentation and recall for each outcome, interviewer fixed effects, and survey version fixed effects. Heterogeneity by education and age estimated in separate regressions.



LOWESS estimates of the relationship between age and the z-score of the POEM index and the three olfactory tests – identification, memory, and discrimination.



LOWESS estimates of the relationship between age and the z-score of the POEM index and the word, picture, and story-based memory assessments



LOWESS estimates of the relationship between age and the z-score of the POEM index stratified by those with heavy tsunami damage exposure and those without heavy tsunami damage exposure.

Appendix Table 1: Calculating POEM

	[1]
	Olfactory Memory Score
Identification Correct	0.37
	[5.56]
Discrimination Correct	0.20
	[2.96]
Constant	7.51

Appendix Table 2: Relationships between memory markers (z-scored) and demographics
Respondents age
45+

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
	Raw Difference				**% Recall Difference:**			
	Constructional Praxis	Brave Man Story	Logical Memory Story	Word Recall	Constructional Praxis	Brave Man Story	Logical Memory Story	Word Recall
(1) Male	0.18	0.022	0.004	-0.151	0.14	0.014	0.044	-0.081
	[3.09]	[0.37]	[0.06]	[-2.11]	[2.40]	[0.22]	[0.72]	[-1.16]
Age	-0.012	-0.004	-0.002	0	-0.01	-0.014	-0.013	-0.006
	[-3.20]	[-1.23]	[-0.58]	[0.07]	[-2.44]	[-3.92]	[-3.34]	[-1.43]
Years of Education	0.004	-0.03	-0.022	-0.015	0.02	0.019	0.027	0.03
	[0.60]	[-4.17]	[-3.14]	[-1.90]	[2.71]	[2.28]	[3.80]	[3.76]

Notes: All outcomes z-scored with mean 0, standard deviation 1. Heteroskedasticity-robust t-statistics reported in brackets. OLS regression coefficients reported conditional on smoking, congestion, time between presentation and recall for each outcome, interviewer fixed effects, and survey version fixed effects. POEM score is calculated as the residual from a regression predicting olfactory memory score with olfactory identification and discrimination score.

Appendix Table 3: Effects of tsunami exposure on memory markers (z-scored), age <65
Respondents age 45-65

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
					% Recall Difference:			
	Olf. Identification Score	Olf. Memory Score	Olf. Discrimination Score	POEM Score	Constructional Praxis	Brave Man Story	Logical Memory Story	Word Recall
Panel A: Exposure based on pre-tsunami residence, district fixed-effects models.								
(1) Heavy Damage Exposure	0.045	-0.187	-0.034	-0.198	0.02	0.025	0.127	0.008
	[0.26]	[-1.42]	[-0.53]	[-2.17]	[0.77]	[0.45]	[3.38]	[0.07]
Panel B: Individual-specific tsunami exposures - swept away in water. Pre-tsunami community fixed-effects models.								
(1) Swept away in the water	0.159	-0.16	-0.053	-0.22	0.05	-0.079	0.18	-0.003
	[1.47]	[-1.41]	[-0.55]	[-1.91]	[0.34]	[-0.85]	[1.21]	[-0.02]

Notes: All outcomes z-scored with mean 0, standard deviation 1. T-statistics clustered at the district level reported in brackets. OLS regression coefficients reported conditional on gender, smoking, congestion, time between presentation and recall for each outcome, interviewer fixed effects, and survey version fixed effects.

Appendix Table 4. Summary statistics

Mean (standard error) of respondents age 45 and older

	[1] Full Sample
Covariates	
% Male	46.6
	[1.4]
Age	56.4
	[0.3]
Years education	7.8
	[0.1]
% Congested	45.8
	[1.4]
% Ever smoke cigarettes	34.3
	[1.4]
% High damage exposure	34.5
Outcomes	
Olfactory Identification Correct (out of 10)	6.3
	[0.1]
Olfactory Memory Correct (out of 20)	11.5
	[0.1]
Olfactory Discrimination Stage	7.8
	[0.1]
POEM Index	0.0
	[0.1]
% Recall difference constructional praxis	-13.8
	[1.0]
% Recall difference brave man story	-47.5
	[1.8]
% Recall difference logical memory story	-37.9
	[1.8]
% Recall difference word recall	-48.3
	[1.4]
Sample Size	1,189

Heteroskedasticity-robust standard errors in brackets

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