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Capacity-limited resources are used for managing sensory degradation and cognitive demands: Implications for age-related cognitive decline and dementia

Adam R. Billig, Nicole C. Feng, Hura Behforuzi, Brittany M. McFeeley, Casey M. Nicastri and Kirk R. Daffner[*]

Laboratory of Healthy Cognitive Aging, Division of Cognitive and Behavioral Neurology, Center for Brain/Mind Medicine, Department of Neurology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, United States

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Older adults with sensory deficits are at higher risk for developing cognitive impairment and dementia. It remains uncertain if the link between sensory and cognitive functioning reflects a common underlying factor or whether sensory deficits directly undermine cognitive processing. This issue was addressed by comparing behavioral and event-related potential responses of 16 older and 16 young adults during a working memory paradigm that parametrically varied visual contrast level (100%, 69%, 22%) and cognitive task load (1–4 face pairs to remember). The groups were well-matched on demographic and neuropsychological variables; however, older adults had worse corrected visual acuity and contrast sensitivity. The study's major finding was an interaction between visual contrast level and task load on performance accuracy (percent of correct responses) and the allocation of resources for decision making/updating (as indexed by the P3b amplitude). The negative impact of degraded visual processing was greater at higher levels of task demand. This result suggests that a shared pool of processing resources is used to mediate cognitive operations and manage the processing of degraded images. The study also demonstrated that older adults reach the limits of their processing capacity at lower levels of task load. The interaction between visual degradation and task demand, accompanied by the age-related reduction in available processing resources highlight the increased vulnerability of older adults. Specifically, an age-associated decline in visual acuity and contrast sensitivity puts older adults at risk for depleting their limited resources in the service of processing degraded visual images. The results of this study underscore the potential

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[*] *Corresponding author*. Division of Cognitive and Behavioral Neurology, Brigham and Women's Hospital, Harvard Medical School, 60 Fenwood Road, Boston, MA 02115, United States.

E-mail addresses: abillig@bwh.harvard.edu (A.R. Billig), nicolefeng@gmail.com (N.C. Feng), hurabehforuzi@gmail.com (H. Behforuzi), bmcfeeley@bwh.harvard.edu (B.M. McFeeley), cnicastri@bwh.harvard.edu (C.M. Nicastri), kdaffner@bwh.harvard.edu (K.R. Daffner).

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importance of optimizing vision in older adults to help mitigate age-associated cognitive decline.

Abbreviations

AMNART	American National Adult Reading Test
CS	Contrast sensitivity
ERP	Event-Related Potentials
MMSE	Mini Mental State Exam
NP	Neuropsychological
PCA	Principal component analysis
P3b-Ave	P3b amplitude from the average waveform data
P3b-PCA	P3b amplitude from the PCA data
RT	Reaction time
TF(a)SF(b)	Temporal factor (a), spatial factor (b)
URE	Uncorrected refractive error
VA	Visual acuity
WM	Working memory
1FP	1 face pair
2FP	2 face pairs
3FP	3 face pairs
4FP	4 face pairs

1. Introduction

With the escalating rise in adults living to advanced ages, an increasing number of individuals are suffering from cognitive decline and dementia (Langa, 2018). Not surprisingly, there is mounting interest in identifying risk factors for cognitive deterioration that can be modified (Daffner, 2010). Models have suggested that delaying the clinical onset of Alzheimer's Disease (AD) by five years has the potential to reduce the prevalence rate by ~50% (Brookmeyer et al., 1998). Even small effects on preserving cognitive abilities may have a large impact in the aggregate. There is substantial evidence that older adults with sensory impairments are at increased risk for developing cognitive impairment and dementia (Baltes & Lindenberger, 1997; Christensen, Mackinnon, Korten, & Jorm, 2001; Hwang et al., 2020; Lindenberger & Baltes, 1994; Lindenberger et al., 2001; Rogers & Langa, 2010; Spierer, Fischer, Barak, & Belkin, 2016). For example, one study found that individuals with baseline impairment in three sensory domains (hearing, vision, and olfaction) had a 15 times greater risk of developing cognitive impairment (measured as an MMSE score of <24/30) over the next 10 years than individuals without evidence of sensory impairment (Fischer et al., 2016).

The current study focused on addressing the reported link between cognitive decline and age-related visual impairment. Normal aging is associated with a decline in both visual acuity (VA) (Jackson & Owsley, 2003; Owsley, 2011; Owsley et al., 1983), which is the ability to distinguish small, high contrast targets, and visual contrast sensitivity (CS) (Greene & Madden, 1987; Nameda, Kawara, & Ohzu, 1989; Owsley et al., 1983; Owsley & Sloane, 1987), which is the ability to distinguish relative differences in luminance (Nio et al., 2002). Age-related decline in VA can be partially attributed to a high prevalence of older adults having uncorrected refractive errors (URE) and using outdated, suboptimal corrective lens prescriptions (Skeel et al., 2003; Tielsch et al., 1990). URE is the single biggest cause of worldwide vision impairment, accounting for 42% of all global vision impairments (Lee & Mesfin, 2019). URE can often be readily optimized through updated prescriptions for eyeglasses or contacts, or through cataract surgery.

Experimentally testing the VA of individuals determines their ability to distinguish visual details of high-contrast targets only under optimal lighting conditions. Testing under these conditions does not fully translate to functional acuity in daily living, where there is often suboptimal luminance and the need to process objects of varying contrast. Measuring an individual's CS provides a more comprehensive assessment of functional acuity (Bansback et al., 2007; Nomura, Ando, Niino, Shimokata, & Miyaki, 2003; Scialfa, 2002). Compared to VA, CS has been demonstrated to be more strongly associated with neuropsychological functioning (Skeel et al., 2003) and performance in daily activities such as judging distances, mobility, driving, and discriminating highway signs (Evans & Ginsburg, 1985; Rubin, Roche, Prasada-Rao, & Fried, 1994; Wood & Owens, 2005). A cohort study investigating community-dwelling older women found that reduced baseline CS was linked to a greater risk developing mild cognitive impairment (MCI) or dementia within a 10-year period. The association remained significant after controlling for known independent risk factors of MCI and dementia (e.g., age, education, smoking, etc.) as well as for self-reported history of glaucoma, age-related macular degeneration, or cataracts, all of which worsen CS (Ward et al., 2018).

Some clinicians already encourage patients to take steps to enhance their vision and hearing to counter the negative impact of sensory deficits on cognition. The issue can be framed in terms of not "wasting" limited cognitive resources on simply trying to detect and decode visual information or sounds. However, to date, the assumption of a direct relationship between resources used to overcome or compensate for sensory deficits and the resources used to manage cognitive demands has not been systematically tested. In a prior investigation, we demonstrated that the robust age-related decline in P3b amplitude to visual targets, an event-related potential (ERP) index of cognitive decision making/updating, disappeared after controlling for VA (Porto et al., 2016). Path analysis indicated that the relationship between age and diminished P3b was mediated by VA, suggesting that conveyance of suboptimal sensory information due to peripheral, not central, deficits may undermine subsequent cognitive processing. A strategy for more directly determining whether there is a causal link between visual impairment and age-related changes in neural activity would be to experimentally degrade stimulus signal or VA and determine the impact on P3b amplitude, as was carried out in the current experiment. Recent studies have suggested that cataract surgery and hearing aid use can alter the trajectory of cognitive decline in healthy older adults (Maharani et al., 2018a, 2018b) Although these results are encouraging, the mechanisms underlying the relationship between age-related sensory and cognitive decline remain unclear.

At least three theoretical models have been proposed to explain the relationship between age-related changes in sensory and cognitive processing: the *common cause hypothesis*, the *sensory deprivation hypothesis*, and the *information degradation hypothesis*. The classic version of the common cause hypothesis suggests that a common, biologically-based factor is responsible for age-related deterioration at all levels of functioning, including sensory and cognitive processing (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). In this model, age-associated sensory impairment does not directly undermine cognitive functioning. Rather, changes in both sensory and cognitive functioning reflect a common underlying cause, and experimentally degrading sensory signals should not influence cognitive processing (Monge & Madden, 2016). In contrast, the sensory deprivation and information degradation hypotheses suggest that impaired sensory functioning has a negative causal effect on the cognitive functioning (Baltes & Lindenberger, 1997; Christensen, Mackinnon, Korten, & Jorm, 2001; Lindenberger & Baltes, 1994; Lindenberger et al., 2001; Salthouse, 1996). One important difference between these two hypotheses involves the time required for degraded sensory inputs to affect cognitive processing. The sensory deprivation hypothesis suggests that over an extended period, a decline in perceptual processing leads to a gradual degradation in neural processors subserving cognition, perhaps by causing individuals to disengage from their environment (Lindenberger & Baltes, 1994; Monge & Madden, 2016). By contrast, the information degradation hypothesis postulates that the delivery of suboptimal sensory information directly leads to impaired higher order processing by downstream regions that results in cognitive loss (Schneider and Pichora-Fuller 2000). Fig. 1 provides relevant schematics for each of these hypotheses. Unfortunately, most of the studies examining the association between cognitive and sensory-perceptual decline due to aging have been correlational, and thus, cannot determine if modifying the strength of a study participant's perceptual signal has an immediate effect on cognitive processing, which would support the information degradation hypothesis, but not be consistent with the predictions made by the other two relevant hypotheses (Monge & Madden, 2016).

If the information degradation hypothesis accurately reflects the underlying relationship between sensory and cognitive processing, then experimental manipulations of visually degraded stimuli should have an immediate impact on cognitive performance for both older and younger adults. One might expect that visually degraded stimuli would have a greater effect on older adults' cognitive performance due to age-related slowing of perceptual processing (Madden, 2001; Salthouse, 1996) as well as to suboptimal top-down mechanisms related to age-associated neural decline (Gazzaley et al., 2005; West, 1996), which cannot adequately compensate for the degraded bottom-up, perceptual signals in older adults. However, age-associated differences in the effect of degraded stimuli have not been consistently observed (Toner et al., 2012).

The current study aimed to address some of the gaps in the literature by comparing behavioral responses and electrophysiological data (ERPs) of both older and young adults during a working memory (WM) task that parametrically varied task load (one to four face pairs to remember) and visual contrast level (100%, 69%, 22%). The P3b, a posteriorly-distributed component, was the main ERP dependent variable. There is evidence that the P3b indexes the decision-making process involved in categorizing an event (Ford, 1978; Kok, 2001; Squires et al., 1973) or updating memory after an event has been categorized (Donchin, 1981; Donchin & Coles, 1988). Its latency is a marker of processing speed to categorize a stimulus and update WM (Donchin, 1981; Luck & Kappenman, 2012; Polich, 2007), while its amplitude provides an index of the resources allocated to execute the task and the amount of information transferred (i.e., reduction of uncertainty) during the operations carried out (Johnson, 1985; Sirevaag, Kramer, Coles, & Donchin, 1989; Sutton et al., 1965; Wickens et al., 1983). In general, increasing task demands result in an augmentation of P3b amplitude until an individual's resources are depleted. The Compensation-Related Utilization of Neural Circuits (CRUNCH) hypothesis suggests that the threshold (or "crunch" point) after which cognitive resources are depleted tends to occur at lower levels of cognitive demand in older adults compared to their younger counterparts (Daffner et al., 2011; Reuter-Lorenz, 2002; Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2010).

The impact of sensory degradation on P3b amplitude is more complex. To the extent that processing degraded images results in greater decision-making uncertainty, one might expect a decline in P3b amplitude even at low levels of task load. However, to the extent that an increase in task difficulty (related to processing degraded images) elicits a greater allocation of resources, one might anticipate an augmentation of P3b amplitude (Ford, Pfefferbaum, Tinklenberg, & Kopell, 1982) up until the point in which resources are depleted. If shared resources are used to manage both increases in task load and reductions in sensory fidelity, one would anticipate that sensory degradation would have a greater impact on P3b amplitude under high task load.

In the current study, we were particularly interested in determining if the results demonstrate an interaction between task load and visual contrast level. If present, it would provide evidence in favor of the information degradation hypothesis and offer further justification for increased efforts to try to modify peripheral sensory deficits to improve cognitive functioning. Moreover, we were interested in investigating whether the pattern and/or magnitude of response was similar for older and young adults. We hypothesized that because, on average, older adults exhibit declines in peripheral visual functioning (Greene & Madden, 1987; Jackson & Owsley, 2003; Owsley, 2011; Owsley et al., 1983), speed of

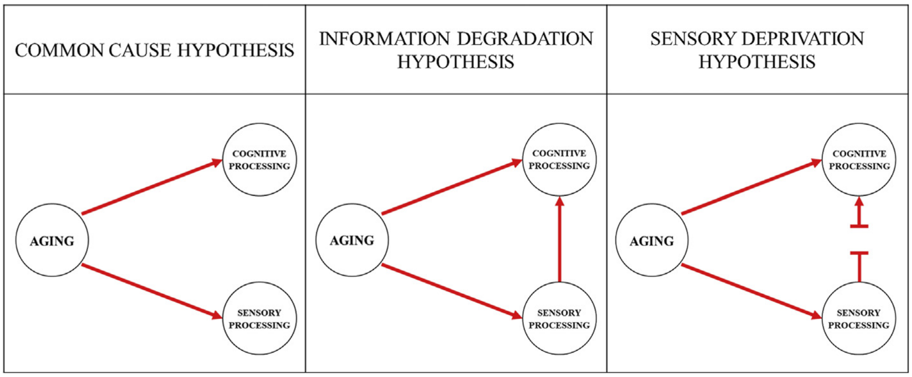

Fig. 1 – Schematics of three hypotheses accounting for the relationship between age-related changes in sensory-perceptual and cognitive processing. The red lines represent causal connections, with the arrow indicating the direction of causality. For the common cause hypothesis, there is no direct link between perceptual processing and cognitive processing. If this hypothesis is accurate, then manipulating sensory processing (e.g., by degrading stimulus signal as done in the current experiment) should not directly influence cognitive processing. For both the information degradation hypothesis and the sensory deprivation hypothesis, there is a direct link between perceptual and cognitive processing. However, for the sensory deprivation hypothesis, the causal mechanism requires a temporal delay, as symbolized by the noncontinuous line between sensory and cognitive processing.

perceptual processing (Faust, Balota, Spieler, & Ferraro, 1999; Madden, 2001; Salthouse 1996, 2000), and top-down compensatory mechanisms (Gazzaley et al., 2005; West, 1996), older subjects would be more sensitive to the impact of sensory degradation. In addition, consistent with the CRUNCH hypothesis, we anticipated that older adults would deplete their resources at lower levels of task demand than young adults.

2. Methods

In this section we report how we determined our sample size, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations and all measures in the study. All data exclusions are noted in section 3.1.

Sample size was estimated primarily based on the means and SDs of the P3 response of our previously studied groups across the adult lifespan (Alperin et al., 2013; Daffner et al., 2011; Mott et al., 2014; Riis et al., 2008). We estimated that a sample size of at least 16 subjects per group would be sufficient to detect a meaningful effect size (.4) with greater than .80 power at an alpha level of .05. Cognitively healthy adult subjects were recruited through flyers posted around the greater Boston area, recruitment at local college campuses, as well as through the Partners Healthcare System online clinical research recruitment portal. All subjects provided written informed consent approved by the Partners Human Research committee.

Prior to inclusion in this study, all potential subjects underwent a detailed screening evaluation that included a structured interview to obtain a medical, neurological, and psychiatric history. To be included in this study, participants had to be between the ages of 18 and 32 (young adults), or 65 and 85 (older adults), be English-speaking, have ≥ 12 years of education, have an estimated IQ ≥ 90 [based on the American National Adult Reading Test (AMNART) (Ryan & Paolo, 1992)], and a Mini Mental State Examination (MMSE) score ≥ 26. Subjects were excluded from this study if they had a history of CNS diseases or major psychiatric disorders based on Diagnostics and Statistical Manual of Mental Disorders (DSM-5) (American Psychiatric Association, 2013), history of clinically significant medical diseases, auditory problems that resulted in an inability to hear or discern verbal instructions, or corrected VA worse than 20/50. All subjects had a screening neurological examination, conducted by a physician, to test for evidence of focal injury. This was not observed in any subject. Subjects were compensated for their time.

To more fully characterize subjects, we conducted neuropsychological (NP) testing and collected self-reported measures. The NP evaluation consisted of the following tests: (1) AMNART (Ryan & Paolo, 1992); (2) MMSE (Folstein et al., 1975) (3) Boston Naming Test (BNT) (Ivnik et al., 1996); (4) Logical Memory I and II (subtests of the Wechsler Memory Scale 4th Edition (WMS-IV)) (Wechsler, 2009); (5) Digit Span Forwards, Backwards, and Sequencing (subtests of Wechsler Adult Intelligence Scale 4th Edition (WAIS-IV) and WMS-IV) (Wechsler 2008, 2009); (6) Digit-Symbol Coding (WAIS-IV) (Wechsler, 2008); (7) Trail-Making Test (TMT) Part A and Part B (Reitan & Wolfson, 1985); (8) Word Fluency Test (Ivnik et al., 1996); (9) Benton Visual Form Discrimination Test (Benton et al., 1983). NP test scores were standardized for each subject using age-matched norms. A composite NP percentile score was calculated for each subject by averaging the percentile performance scores (based on age-appropriate norms) from the following assessments: Logical Memory II, Digit Span (forwards, backwards, and sequencing), Digit-Symbol Coding, TMT Part A, TMT Part B, and the Word Fluency Test. For each subject, we collected self-reported measures that included: (1) demographic information; (2) for young subjects, Beck Depression Inventory (BDI) (Beck et al., 1988); for old subjects, Geriatric Depression Scale (GDS) (Yesavage et al., 1983). Corrected VA was measured for each subject using Snellen wall chart (Sue, 2007), and CS was measured using the Mars Letter Contrast Sensitivity Test (Dougherty et al., 2005).

2.1. *Experimental procedure*

The experiment consisted of a WM paradigm that parametrically varied task load (quantity of face pairs to be remembered) and visual stimulus degradation (contrast level). There were four levels of task load (one to four face pairs) and three levels of contrast (100%, 69%, 22%). ERPs were recorded via a 128- electrode EEG, while the subject completed the experimental paradigm.

FaceGen Modeller 3.5 was used to generate faces with a high degree of realism (see Fig. 2). The faces represented four different racial groups (African (AF); East Asian (EA); South Asian (SA); and European (EU)). The age for each face was standardized to 25 years old. The face stimuli were digitally filtered using built-in functions within the Python Software programming language. The contrast filters used (69% and 22%) were chosen because they reflect half-log differences in contrast that have been used in prior studies (Toner et al., 2012).

Participants were seated approximately 60 inches from a high-resolution monitor. Faces presented on the monitor were approximately six inches wide and nine inches tall. The order of task load presentation (1 face pair (1FP), 2 face pairs (2FP), 3 face pairs (3FP), 4 face pairs (4FP)) was counterbalanced across subjects in a Latin square design. For each level of task load, participants completed three blocks of trials in succession. Each trial block included a study period and a testing period, the latter of which consisted of 84 stimulus trials. At study, faces were presented in pairs (left and right of each other) on the monitor at 100% contrast. Although paired faces were different, they shared the same gender and racial group. Participants were given two consecutive 20-s intervals to study each face pair. One face in each of the pairs was designated as the *target*. After the study period, subjects were shown a slide with text asking them to press a button when they were ready to proceed to testing. Typically, approximately 10 s elapsed between the study period and the onset of testing. During the testing period, subjects were shown one face at a time and were instructed to respond to target faces by clicking the left mouse button and to non-target faces by clicking the right mouse button (i.e., **forced choice** paradigm with .5 target and .5 non-target). The three contrast levels (100%, 69%, 22%) were evenly distributed within each block of 84 trials. Participants were told that during testing some of the images might appear less clear than others, and were encouraged to respond as accurately and as quickly as possible. During the study period before each of the three blocks for a particular task load, face pairs were presented in the same order. During the testing period, individual faces were presented in random order. Each face was shown for 1000 ms. The inter-stimulus interval (ISI) varied randomly between 1400 and 1700 ms, during which time a white fixation cross was shown.

A practice trial was conducted prior to the experiment to ensure that the subject demonstrated an understanding of the task. The practice trial only displayed a single face pair at the 100% contrast level and consisted of two 20-s study intervals, and 16 trials in a single block. ERPs were not recorded during practice trials. Fig. 2 represents a timeline of the experimental procedure.

To produce an even distribution of race and gender, two sets of 10 face pairs were created. One set of 10 face pairs contained exclusively male faces, with three pairs of AF, three pairs of EA, two pairs of SA, and two pairs of EU. The other set of 10 face pairs contained exclusively female faces, with two pairs of AF, two pairs of EA, three pairs of SA, and three pairs of EU. The specific face pairs used for each of the four task loads varied across subjects (e.g., the same face pair might be the first pair presented under the 2FP load for one subject and the third pair presented under the 4FP load for another subject). This was accomplished by creating two versions within each set of 10 face pairs that assigned different FPs to be used for each task load. We also varied which face from each pair was designated as the target face, such that for half the subjects one face of the pair was designated a target face, while

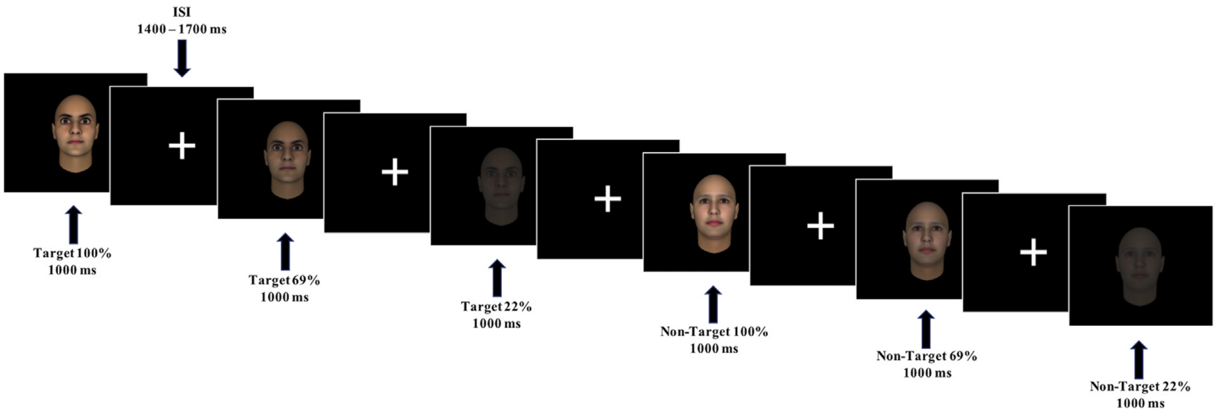

Fig. 2 – Illustration of an experimental run under the 1FP load condition. The target and non-target stimuli represent two South Asian male faces generated using FaceGen Modeller 3.5 software. Faces were presented at three different levels of contrast (100%, 69%, 22%). There were three blocks under each task load, with 84 stimuli presented in each block. All face stimuli were shown for 1000 ms, with an ISI varying between 1400 and 1700 ms. This was a forced choice paradigm with .5 target and .5 non-target stimuli.

for the other half of subjects the alternative face of the pair was designated a target. No part of the study procedures was pre-registered in an institutional registry prior to the research being conducted.

2.2. *Behavioral data*

E-Prime 2.0 software was used to present the WM paradigm and collect behavioral data. A valid response was defined as any button press between 200 ms and 2400 ms after the face appeared on the screen. An invalid response was any button press before 200 ms of stimulus display (too early) or after 2400 ms (too late). A correct response was a valid response that accurately identified the stimulus as a target or non-target. Behavioral data were collected in the form of performance accuracy (target hits, non-target hits, target misses, non-target misses, no response, invalid response (too early, too late)) and mean reaction time (RT) (target hits, non-target hits).

2.3. *ERP recordings and analysis*

Methods used in the ERP data collection and analysis were similar to those described in previous publications from our laboratory (e.g., Behforuzi et al., 2019; Porto et al., 2016). EEG data were collected using an ActiveTwo electrode cap (Behavioral Brain Sciences Center. Birmingham, UK) that held to the scalp an array of 128 Ag–AgCl Biosemi (Amsterdam, The Netherlands) "active" electrodes whose locations were based on a pre-configured montage. In addition to the 128 electrodes on the scalp, 6 mini bio-potential electrodes were placed over the left and right mastoid region as reference channels, beneath each eye, and next to the outer canthi of the eyes to check for eye blinks and vertical and horizontal eye movements.

EEG data were analyzed using ERPLAB (Lopez-Calderon & Luck, 2014) and EEGLAB (Delorme & Makeig, 2004) tool boxes that operate within the MATLAB framework. Raw EEG data were resampled from 512 to 256 Hz and referenced off-line to the average value of the right and left mastoid sites. EEG signals were filtered using an IIR filter with a bandwidth of .03–40 Hz (12 dB/octave roll-off). The sampling epoch for each trial lasted 1200 ms, including a 200-ms prestimulus period used to baseline correct the ERP epochs. Eye artifacts were removed through an independent component analysis. Individual bad channels were identified through visual inspection and those that revealed consistently different patterns of activity from surrounding channels were corrected with the EEGLAB interpolation function. Trials were discarded from the analyses if they contained baseline drift or movement artifacts greater than 90 μV. Only trials with correct responses (target hits and non-target hits) were included in the analysis. Across the 24 conditions (4 load x 3 contrast x 2 stimulus types), the mean number of trials retained after artifact rejection was 37.8, with a standard deviation of 2.3, and a range of 29.9–37.8. No part of the study analysis was pre-registered in an institutional registry prior to the research being conducted.

2.4. *Average waveforms*

The focus of this paper is on the P3 component of ERP. The local peak latency of the P3 was measured for each group within the interval of 350–700 ms. The amplitude of P3 was measured as the mean amplitude within the temporal interval defined as the mean midline (Fz, Cz, Pz) local peak latency of each group ± 60 ms. For older adults, the mean midline local peak latency was 585 ms, thus the range used to measure P3 mean amplitude for each older subject was 525 ms–645 ms. For younger adults, the mean midline local peak latency was 560 ms, thus the range used to measure P3 mean amplitude for each younger was 500 ms–620 ms.

2.5. *Temporospatial principal component analysis (PCA)*

In addition to measuring average waveforms at midline electrodes, we performed a principal component analysis (PCA) of the data. PCA is a data-driven method that decomposes ERP waveforms into their underlying components and is particularly useful in separating spatially and/or temporally overlapping components. Temporospatial PCA takes advantage of this method's ability to parse components both temporally and spatially by breaking down each temporal principal component into a series of spatially distinct components (Dien et al., 2003; Luck & Kappenman, 2012). Following the recommendations of Dien (2012) a temporospatial PCA (temporal PCA followed by a spatial PCA on each identified temporal factor) was conducted on averaged trials for each individual subject at all 134 electrode sites. ERPs to both target and non-target stimuli were included in the analysis. Utilizing the ERP PCA Toolkit 2.39 (Dien, 2010), a Promax rotation was used and a covariance matrix and Kaiser normalization were applied to the data. Our focus was on the temporospatial factor whose timing and topographic distribution was consistent with the P3b component.

2.6. *Statistical analysis*

Statistical analysis was conducted using the IBM SPSS Version 25. Comparisons between the two age groups of demographic data, neuropsychological test results, corrected VA and CS were made using independent sample *T*-tests, and, where appropriate (i.e., gender), non-parametric Mann–Whitney *U*-test. Behavioral (performance accuracy, RT), P3 average waveform (local P3 peak latency, P3b amplitude), and PCA data were analyzed with repeated measure ANOVA with Greenhouse-Geisser corrections (Greenhouse & Geisser, 1959). Within subject factors included task load (1FP, 2FP, 3FP, 4FP), contrast level (100%, 69%, 22%), stimulus type (target, non-target), and for P3 average waveform data, electrode site (Fz, Cz, Pz). The between-subject factor was age group (older, young). Results were considered significant at $p < .05$. For analyses involving multiple comparisons, any uncorrected p-values of <.05 would be noted that did not remain significant after employing the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995), with a false discovery rate set at .1 (none were observed). In addition, effect sizes (Cohen's d) were calculated for outcome variables that demonstrated a significant interaction between contrast level and task load by comparing the effect of contrast level (100% vs. 22%) under the 1FP condition to the effect of contrast level (100% vs. 22%) under the 4FP condition.

3. Results

3.1. *Participants*

We are reporting on data collected from 32 subjects; 16 older adults (mean age 70.1 ± 5.0 years old) and 16 young adults (mean age 21.6 ± 2.7 years old). An additional two subjects (one older and one young adult) completed the study, but were not included in the analysis due to technical problems during the collection of their experimental data.

Table 1 provides a summary of subject characteristics, which includes demographic information, MMSE, verbal IQ (estimated by AMNART), percentile NP test performance, corrected VA, and CS. There was no difference between older and younger adults in terms of gender, years of education, and scores on the AMNART, MMSE, or the percentile NP test performance, although older adults tended to do better ($p < .08$). For VA, there was an effect of age group ($p < .001$), with older adults having worse corrected VA than younger adults. There also was an effect of age group for contrast sensitivity ($p = .005$) with older adults having lower CS than younger adults. Although VA and CS were worse in older adults, their impairments were mild.

3.2. *Behavioral data*

3.2.1. *Performance accuracy*

Performance accuracy was defined in terms of the percent of correct responses (i.e., hits) to target and non-target stimuli. Fig. 3 presents a bar graph summarizing the results for accuracy in response to target stimuli. There was an effect of contrast level ($F_{(2,60)} = 25.33$, $p < .001$, $\eta_p^2 = .46$) and task load ($F_{(3,90)} = 18.2$, $p < .001$, $\eta_p^2 = .38$), but not of age group or stimulus type ($ps > .11$). The contrast level effect was due to lower accuracy at the 22% contrast level than the 69% level ($p < .001$) or 100% level ($p < .001$), with no difference between the latter two contrast levels ($p > .60$). The load effect was due to higher accuracy at 1FP than at 2FP ($p = .014$), which in turn was larger than at 3FP ($p < .001$) and at 4FP ($p < .001$), with no difference between the latter two task loads ($p > .29$) (1FP > 2FP > 3FP = 4FP).

Particularly relevant to the aims of the study, was the **interaction between task load and contrast level** ($F_{(6,180)} = 2.99$, $p = .026$, $\eta_p^2 = .09$). This interaction was present because the magnitude of the effect of contrast level was greater at higher task loads. The contrast level effect on performance accuracy at 1FP was $F_{(2,60)} = 6.60$, $p = .004$, $\eta_p^2 = .18$; at 2FP, $F_{(2,60)} = 12.2$, $p < .001$, $\eta_p^2 = .29$; at 3FP, $F_{(2,60)} = 10.9$, $p = .001$, $\eta_p^2 = .27$, and at 4FP, $F_{(2,60)} = 20.9$, $p < .001$, $\eta_p^2 = .41$. There were significant differences in the magnitude of the contrast level effect between 1FP and 4FP ($p < .001$, $\eta_p^2 = .24$) and between 1FP and 3FP ($p = .015$, $\eta_p^2 = .15$), with no other reliable differences ($ps > .14$). The interaction between task load and contrast level was not modified by age ($p > .66$). However, there was a trend towards an interaction between task load and age group ($F_{(3,90)} = 2.36$, $p = .073$, $\eta_p^2 = .08$). This trend was due to young adults outperforming older adults at 4FP ($F_{(1,30)} = 4.11$, $p = .052$, $\eta_p^2 = .121$), with no difference between the two groups at 1FP, 2FP, 3FP ($ps > .12$). The task load effect was also modified by stimulus type ($F_{(3,90)} = 3.14$, $p = .032$, $\eta_p^2 = .10$). This interaction was present because there was no stimulus type effect at 1FP, 2FP, or 3FP ($ps > .16$), however, there was a stimulus type effect at 4FP ($F_{(1,30)} = 5.17$, $p = .030$, $\eta_p^2 = .15$). At 4FP, subjects responded more accurately to target stimuli, than non-target stimuli.

Table 1 – Demographic data (mean (SD)).

	Older (n = 16)	Young (n = 16)	P-Value
Age	70.1 (5.0)	21.6 (2.7)	<.001
Gender (M/F)	(5/11)	(8/8)	.38
Education Level (years)	16.1 (1.9)	15.1 (1.5)	.32
MMSE	29.0 (1.1)	28.5 (.8)	.20
AMNART	125.6 (4.7)	124.6 (4.2)	.29
Neuropsychological Test Performance (%ile)	70.4 (16.2)	59.2 (18)	.074
Visual Acuity (Corrected)	.98 (.18)	1.20 (.10)	.001
Mars Letter Contrast Sensitivity	1.76 (.05)	1.83 (.07)	.005

MMSE = Mini Mental State Examination. Score range: [0–30].

AMNART = American National Adult Reading Test. Score range: [75–131].

Neuropsychological Test Performance (%ile): Composite neuropsychological test score calculated by averaging the percentile performance (based on age-appropriate norms) on the following tests: Logical Memory II, Digit Span, (forwards, backwards, and sequencing), Digit-Symbol Coding, TMT Part A, TMT Part B, and Word Fluency Test.

Visual Acuity Score Range: [.1–1.25] (20/16 = 1.25; 20/20 = 1.00; 20/25 = .80; 20/30 = .67, etc).

Mars Letter Contrast Sensitivity Score Range: [.00–1.92].

3.2.2. *Mean reaction time*

Fig. 4 presents a bar graph summarizing the results for mean RT in response to target stimuli. There was an effect of

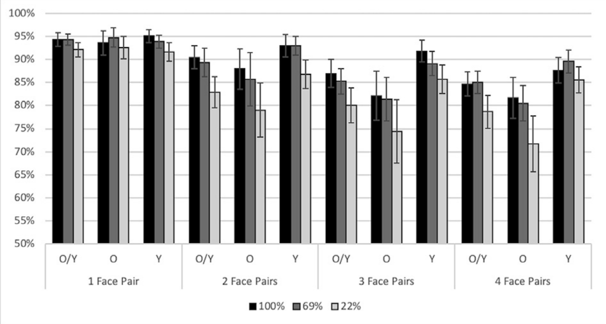

Fig. 3 – Performance accuracy (% correct responses), mean ± SEM in response to target stimuli at each level of task load (1FP, 2FP, 3FP, 4FP) at each level of contrast (100%, 69%, 22%) for older and young (O/Y) adults collapsed across both age groups, and for older (O) and young (Y) adults separated by age group.

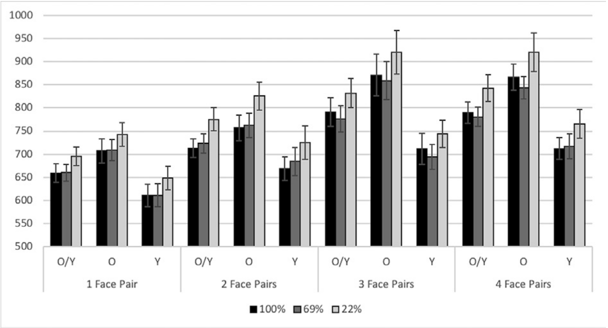

Fig. 4 – Mean reaction time (ms), mean ± SEM, in response to target stimuli at each level of task load (1FP, 2FP, 3FP, 4FP) at each level of contrast (100%, 69%, 22%) for older and young (O/Y) adults collapsed across both age groups, and for older (O) and young (Y) adults separated by age group.

contrast level ($F_{(2,60)} = 47.40$, $p < .001$, $\eta_p{}^2 = .61$), task load ($F_{(3,90)} = 34.83$, $p < .001$, $\eta_p{}^2 = .54$), stimulus type ($F_{(1,30)} = 13.41$, $p = .001$, $\eta_p{}^2 = .31$), and age group ($F_{(1,30)} = 14.65$, $p = .001$, $\eta_p{}^2 = .33$). RTs were longer in response to stimuli at 22% contrast than at 69% contrast ($p < .001$) or at 100% contrast ($p < .001$), with no difference between the latter two contrast levels ($p > .11$). RTs were shorter at 1FP than at 2FP ($p < .001$), which in turn was shorter than at 3FP ($p = .003$) and at 4FP ($p < .001$), with no difference between the latter two levels of load ($p > .059$) (1FP < 2FP < 3FP = 4FP). Non-target stimuli elicited longer RTs than target stimuli. RTs were also longer for older subjects than younger subjects. An interaction was observed between task load and age group ($F_{(3,90)} = 3.40$, $p = .03$, $\eta_p{}^2 = .10$). This was due to the magnitude of the task load effect being smaller for older adults ($F_{(3,45)} = 16.56$, $p < .001$, $\eta_p{}^2 = .53$) than young adults ($F_{(3,45)} = 36.12$, $p < .001$, $\eta_p{}^2 = .71$). For older adults, the load effect was due to shorter RTs at 1FP than at 2FP ($p = .014$), which in turn was shorter than at 3FP ($p = .017$) and at 4FP ($p = .001$), with no difference between the latter two task loads ($p > .98$) (1FP < 2FP < 3FP = 4FP). For young adults, the load effect was also due to shorter RTs at 1FP than at 2FP ($p < .001$), which in turn was shorter than at 3FP ($p = .048$) and at 4FP ($p < .001$), with no difference between the latter two task loads ($p > .24$) (1FP < 2FP < 3FP = 4FP).[1]

There was also an interaction between stimulus type and age group ($F_{(1,30)} = 7.33$, $p = .011$, $\eta_p{}^2 = .20$). This interaction was present because there was a stimulus type effect for older subjects ($F_{(1,15)} = 14.35$, $p = .002$, $\eta_p{}^2 = .49$), but not for young subjects ($p > .39$). For older subjects, non-target stimuli elicited longer RTs than target stimuli. There was no interaction between task load and contrast ($p > .18$).

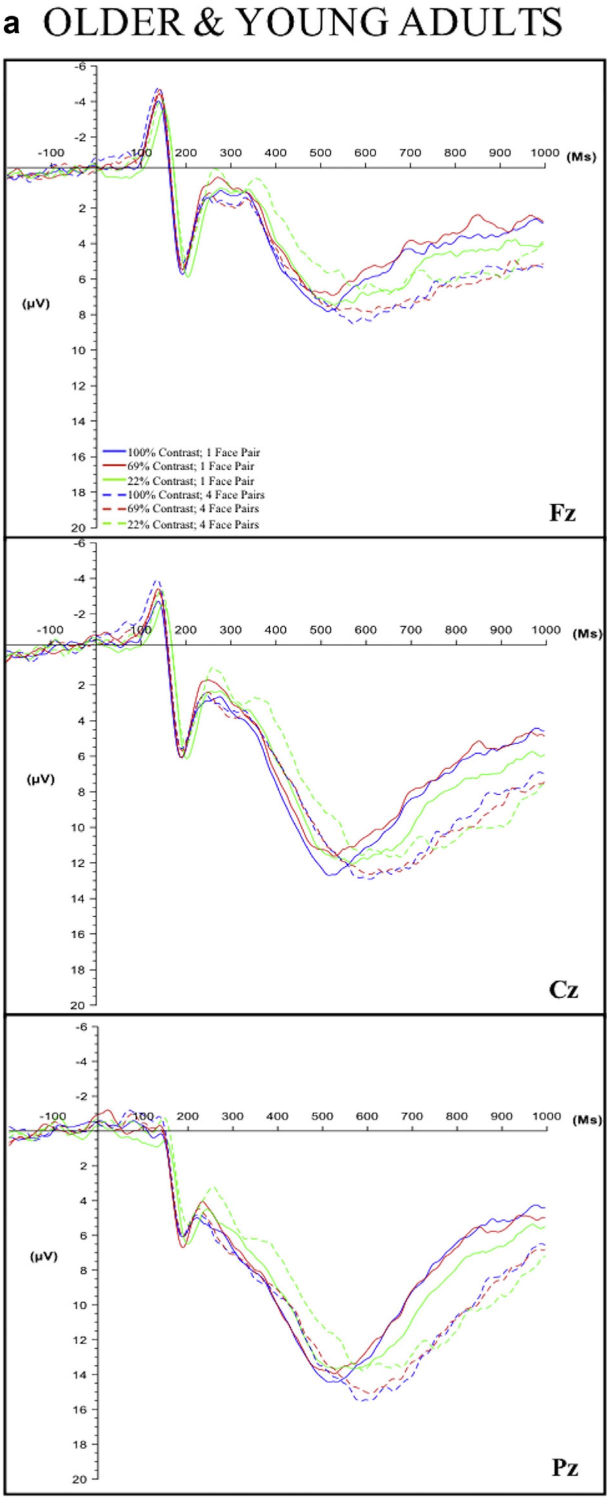

Fig. 5 – a: Illustration of grand average ERP waveforms in response to target stimuli for 1FP (100% contrast, 69% contrast, 22% contrast) and for 4FP (100% contrast, 69% contrast, 22% contrast), for older and young adults (collapsed across both age group). b: Illustration of grand average ERP waveforms in response to target stimuli for 1FP (100% contrast, 69% contrast, 22% contrast) and for 4FP (100% contrast, 69% contrast, 22% contrast), for older and young adults (separated by age groups). Note in a and b, Fz top boxes, Cz middle boxes, Pz bottom boxes.

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[1] An alternative way to account for this interaction is to note that the magnitude of the prolongation of RT in older adults relative to young adults was greater at higher task loads (3FP and 4FP) than at lower task loads (1FP and 2FP). The age group effect at 1FP was $F_{(1,30)} = 9.52$, $p = .004$, $\eta_p{}^2 = .24$; at 2FP, $F_{(1,30)} = 7.20$, $p = .012$, $\eta_p{}^2 = .19$; at 3FP, $F_{(1,30)} = 13.40$, $p = .001$, $\eta_p{}^2 = .31$; and at 4FP, $F_{(1,30)} = 16.34$, $p < .001$, $\eta_p{}^2 = .35$.

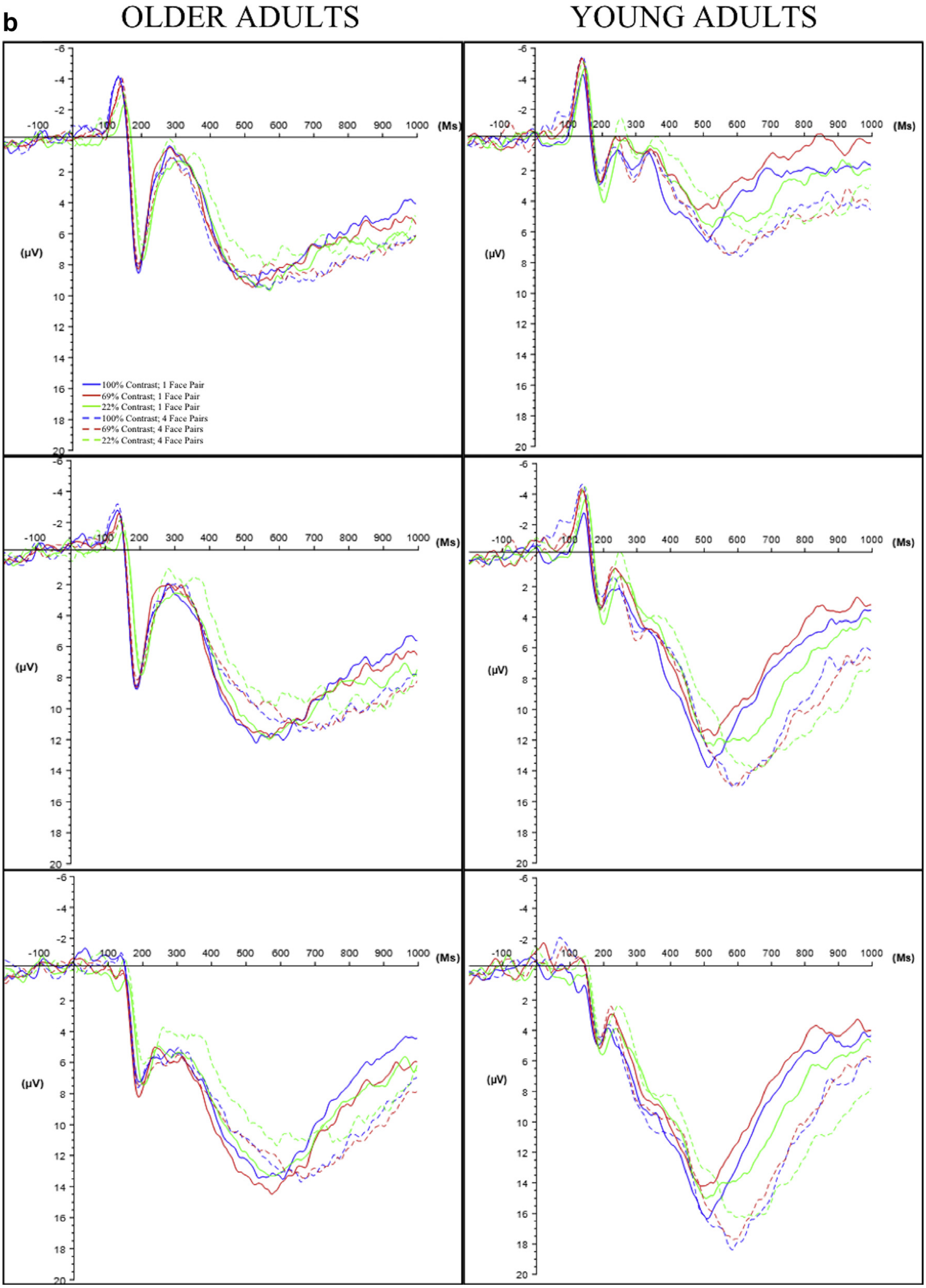

Fig. 5 — (*continued*).

3.3. *Electrophysiological data*

Fig. 5 presents the grand average waveforms in response to target stimuli at each of the three midline electrode sites (Fz, Cz, Pz) for older and young adults collapsed across both age groups (5a) and separated by age groups (5b). Supplemental Figures A.1, A.2, and A.3 illustrate the grand average waveforms in response to non-target stimuli for older and young adults collapsed across both age groups (A.1), older adults only (A.2) and young adults only (A.3).

3.3.1. *P3 local peak latency*

Fig. 6 presents a bar graph illustrating mean local P3 peak latency in response to target stimuli at the midline electrode sites (Fz, Cz, Pz) for older and young subjects. There was an effect of contrast level ($F_{(2,60)} = 19.08$, $p < .001$, $\eta_p^2 = .39$), task load ($F_{(3,90)} = 9.75$, $p < .001$, $\eta_p^2 = .25$), and electrode site ($F_{(2,60)} = 8.74$, $p = .001$, $\eta_p^2 = .23$), but not of age group or stimulus type ($ps > .29$). P3 latency was prolonged at the lowest contrast level, with the peak latency at 22% contrast being longer than at 100% contrast ($p < .001$) or 69% contrast ($p < .001$), with no difference between the latter two contrast levels ($p > .93$). P3 latency was also prolonged at higher task loads, with the peak latency at 1FP being shorter than at 2FP ($p = .002$), at 3FP ($p < .001$), or at 4FP ($p = .001$), with no difference between the latter three load levels ($ps > .14$). For the electrode site effect, the P3 latency at the Cz electrode was longer than at the Pz ($p = .007$) or the Fz ($p < .001$) electrodes, with no difference between the latter two electrode sites ($p > .13$). Although there was no interaction between task load and contrast level ($p > .29$), the effect of task load was modified by age group ($F_{(3,90)} = 3.16$, $p = .041$, $\eta_p^2 = .10$) due to the task load effect being observed in young adults, ($F_{(3,45)} = 21.27$, $p < .001$, $\eta_p^2 = .59$) but not in older adults ($p > .39$). In young adults, P3 latency was prolonged at higher task loads, with 1FP having a shorter P3 latency than 2FP ($p = .002$), which in turn was shorter than at 3FP ($p = .002$) and at 4FP ($p = .010$), with no difference between the latter two levels of load ($p > .60$) (1FP < 2FP < 3FP = 4FP).

The effect of contrast level was also modified by age group ($F_{(2,60)} = 7.81$, $p = .002$, $\eta_p^2 = .21$). Although young adults had a contrast level effect ($F_{(2,30)} = 19.4$, $p < .001$, $\eta_p^2 = .56$), older adults only exhibited a trend towards a contrast level effect ($F_{(2,30)} = 3.46$, $p = .052$, $\eta_p^2 = .19$). In young adults, P3 latency was longer at 22% contrast than 69% contrast ($p < .001$) or 100% contrast ($p = .001$), with no difference between the latter two contrast levels ($p > .22$). In older adults, P3 latency was longer at 22% contrast than 100% contrast ($p = .034$), with no reliable difference between 100% contrast and 69% contrast ($p > .07$) or between 69% contrast and 22% contrast ($p > .30$).

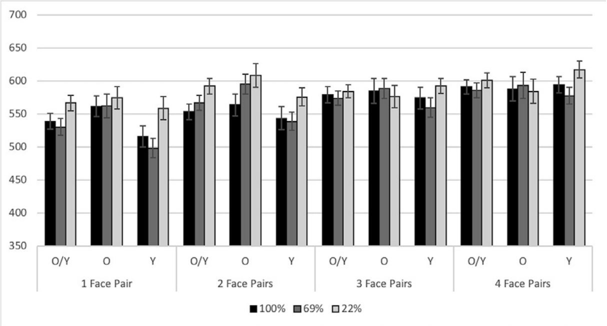

Fig. 6 – Midline P3 local peak latency (ms), mean ± SEM, in response to target stimuli at each level of task load (1FP, 2FP, 3FP, 4FP) at each level of contrast (100%, 69%, 22%) for older and young (O/Y) adults collapsed across both age groups, and for older (O) and young (Y) adults separated by age group.

3.3.2. *P3 mean amplitude*

Supplemental Figure A.4 presents topographical maps of the mean amplitude within the P3 measurement window in response to target stimuli for older and young adults at different levels of contrast and task load. Fig. 7 is a bar graph illustrating mean P3 amplitude in response to target stimuli at the midline electrode sites (Fz, Cz, Pz) for older and young subjects. There was an effect of contrast level ($F_{(2,60)} = 8.00$, $p = .002$, $\eta_p^2 = .21$) and electrode site ($F_{(2,60)} = 46.62$, $p < .001$, $\eta_p^2 = .61$), but not of age group, task load, or stimulus type ($ps > .13$). The contrast level effect was due to P3 amplitude being greater at 100% contrast than 69% contrast ($p = .017$) or 22% contrast ($p = .001$), with no reliable difference between the latter two ($p > .05$). The effect of contrast level was not modified by age group, electrode site, or stimulus type ($ps > .16$). Of particular relevance to the goals of this study, was the interaction between task load and contrast level ($F_{(6,180)} = 2.54$, $p = .03$, $\eta_p^2 = .08$), which was not further modified by age, electrode site, or stimulus type ($ps > .10$). This interaction was present because the impact of lower contrast levels only became apparent at higher levels of task load. For 1FP, there was no contrast level effect ($p > .20$). However, for 2FP, 3FP, and 4FP, there was a contrast level effect ($F_{(2,60)} = 10.60$, $p < .001$, $\eta_p^2 = .26$), which did not differ across these three task loads (no task load by contrast level interaction ($p > .43$).[2] The contrast level effect for 2FP, 3FP, and 4FP was present because the P3 amplitude at 100% contrast was greater than at 22% contrast ($p < .001$), with a trend towards P3 amplitude at 100% being greater than at 69% ($p < .08$). P3 amplitude at 69% contrast was greater than at 22% ($p = .009$), as well.

The effect of electrode site was due to the P3 amplitude at Pz being larger than at Cz ($p < .001$), which in turn was larger than at Fz ($p < .001$) (Pz > Cz > Fz). The electrode site effect was modified by age group ($F_{(2,60)} = 10.15$, $p = .001$, $\eta_p^2 = .25$), task load ($F_{(6,180)} = 2.44$, $p = .037$, $\eta_p^2 = .08$), and stimulus type ($F_{(2,60)} = 2.17$, $p < .001$, $\eta_p^2 = .29$), but not by contrast level

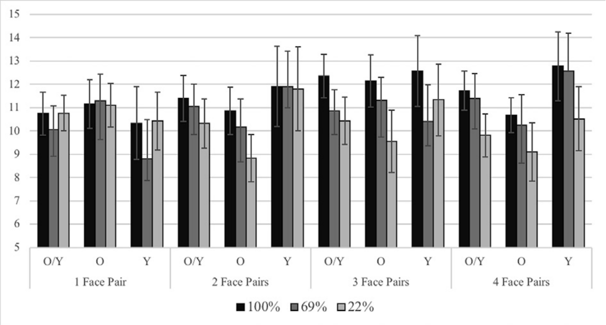

Fig. 7 – Midline mean P3 amplitude (μV), mean ± SEM, in response to target stimuli at each level of task load (1FP, 2FP, 3FP, 4FP) at each level of contrast (100%, 69%, 22%) for older and young (O/Y) adults collapsed across both age groups, and for older (O) and young (Y) adults separated by age group.

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[2] Note, there was an interaction between task load and contrast level when analyzing 1FP vs. 2FP ($p = .021$, $\eta^2 = .13$), 1FP vs. 3FP ($p = .01$, $\eta^2 = .15$), and 1FP vs. 4FP ($p = .023$, $\eta^2 = .12$).

($p > .38$). The electrode site by age group interaction was due to the effect of electrode site being of greater magnitude in younger subjects ($F_{(2,30)} = 55.1$, $p < .001$, $\eta_p{}^2 = .79$), than in older subjects ($F_{(2,30)} = 6.44$, $p = .016$, $\eta_p{}^2 = .30$). The electrode site by task load interaction was due to the smaller magnitude of the electrode site effect at 4FP ($F_{(2,60)} = 42.99$, $p < .001$, $\eta_p{}^2 = .59$) than 1FP ($F_{(2,60)} = 47.12$, $p < .001$, $\eta_p{}^2 = .61$) or 2FP ($F_{(2,60)} = 46.31$, $p < .001$, $\eta_p{}^2 = .61$). The electrode site by stimulus type interaction was due to the stimulus type effect at Cz ($F_{(1,30)} = 4.52$, $p = .042$, η^2 $\eta_p{}^2 = .13$), and at Pz ($F_{(1,30)} = 10.98$, $p = .002$, $\eta_p{}^2 = .27$), but not at Fz ($p > .38$). At the Cz and Pz electrode sites, target stimuli elicited a larger P3 amplitude than did non-target stimuli.

There also was an interaction between task load and age group ($F_{(3,90)} = 3.94$, $p = .02$, $\eta_p{}^2 = .12$). A task load effect was observed in young adults ($F_{(3,45)} = 3.79$, $p = .027$, $\eta_p{}^2 = .20$), but not older adults ($p > .38$). For young subjects, the magnitude of P3 amplitude increased as a function of increased load. The P3 amplitude at 1FP was smaller than at 2FP ($p = .004$) or at 4FP ($p = .008$). There were no reliable differences in P3 amplitude between 1FP and 3FP ($p > .22$), or between 2FP, 3FP, and 4FP ($ps > .28$). The task load by age group interaction was further modified by electrode site ($F_{(6,180)} = 5.12$, $p < .001$, $\eta_p{}^2 = .15$). The task load by age group interaction was present at electrode sites Cz ($F_{(3,90)} = 3.78$, $p = .022$, $\eta_p{}^2 = .11$) and Pz ($F_{(3,90)} = 7.29$, $p = .001$, $\eta_p{}^2 = .20$), but not at Fz ($p > .24$).

3.3.3. *Principal component analysis*

A temporospatial PCA of the whole data set yielded 144 factor combinations [12 temporal factors (TFs), each with 12 spatial factors (SFs)]. The components that accounted for greater than 3% of the total variance were reviewed (see supplementary Figure A.5 which illustrates each of these factors). Based on visual inspection of the timing and topographic distribution of the temporospatial factors, TF03SF01 (667 ms) most likely represented the P3b component (which will be abbreviated as P3b-PCA). Fig. 8 illustrates scalp topographies of TF03SF01 in response to target stimuli for older and young adults at different levels of contrast and task load.

Fig. 9 presents a bar graph of the P3b-PCA amplitude in response to target stimuli for older and young adults at different levels of contrast and task load. There was no overall effect of contrast level, task load or stimulus type ($ps > .26$). Interactions were observed between **task load and contrast level** ($F_{(6,180)} = 3.31$, $p = .009$, $\eta_p{}^2 = .10$), contrast level and age

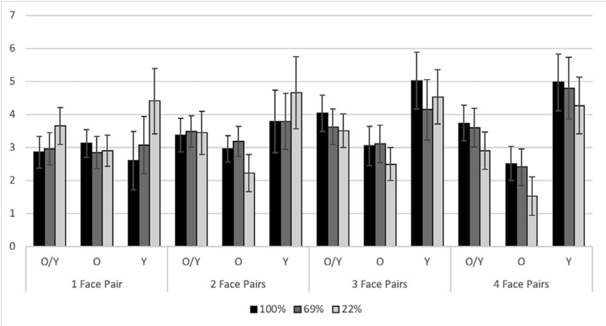

Fig. 9 – P3b-PCA mean amplitude (μV), mean ± SEM, in response to target stimuli at each level of task load (1FP, 2FP, 3FP, 4FP) at each level of contrast (100%, 69%, 22%) for older and young (O/Y) adults collapsed across both age groups, and for older (O) and young (Y) adults separated by age group.

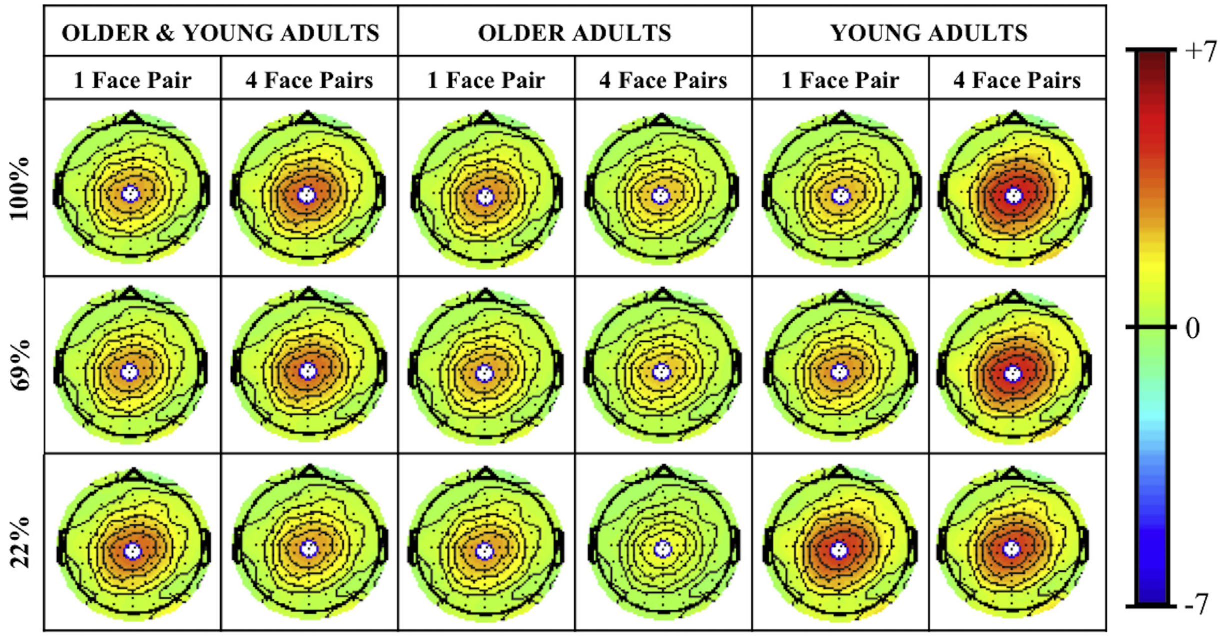

Fig. 8 – Scalp topographies of the PCA component (Temporal Factor 3, Spatial Factor 1) consistent with the P3b in response to target stimuli for 1FP (100% contrast, 69% contrast, 22% contrast) and for 4FP (100% contrast, 69% contrast, 22% contrast), for older and young adults collapsed across both age groups, and for older and young adults separated by age group. Scale is from −7 to 7 μV.

group ($F_{(2,60)} = 5.44$, $p = .017$, $\eta_p^2 = .15$), and task load and age group ($F_{(3,90)} = 4.41$, $p = .011$, $\eta_p^2 = .13$).

The interaction between task load and contrast level was present because the pattern of the effect of contrast level for 1FP ($F_{(2,70)} = 4.92$, $p = .018$, $\eta_p^2 = .14$) was in the opposite direction to that for 4FP ($F_{(2,60)} = 2.56$, $p = .09$, $\eta_p^2 = .08$), with no effect of contrast level for the intervening face pair loads ($ps > .36$). At 1FP, the 22% contrast level elicited a larger amplitude than either the 100% contrast level ($p = .032$) or 69% contrast level ($p = .014$), with no difference between the latter two contrast levels ($p > .89$). However, at 4FP, the trend was in the reverse direction, with the 100% contrast level eliciting a larger amplitude than the 22% contrast level ($p = .064$), with no difference between 69% and 100% contrast ($p > .28$), or between 69% and 22% contrast ($p > .15$).

Similar to the P3b mean amplitude from the average waveform data (which will abbreviated as P3b-Ave), the task load by age group interaction for P3b-PCA was driven by a task load effect in younger adults ($F_{(3,45)} = 8.34$, $p < .001$, $\eta_p^2 = .36$), but not in older adults ($p > .71$). In young subjects, the magnitude of the response increased as a function of increasing task load, with the response to 1FP being of lower amplitude than to 2FP ($p = .002$), 3FP ($p = .004$) or 4FP ($p < .001$), with no difference between the latter three levels of load ($ps > .2$). The interaction between contrast level and age group was present due to a contrast level effect in older adults ($F_{(2,30)} = 3.96$, $p = .044$, $\eta_p^2 = .22$), but not in younger adults ($p > .16$). For older subjects, the amplitude was smaller in response to lower contrast, with the 22% contrast level eliciting a lower amplitude than 100% ($p = .048$) or 69% ($p = .049$), with no difference between the latter two contrast levels ($p > .79$).

3.3.4. *Estimation of effect sizes*

A major objective of this study was to determine if there were interactions between task load and contrast level, which were found for accuracy, P3b-Ave amplitude and P3b-PCA amplitude. To estimate the effect size of these interactions, Cohen's d was calculated by comparing the effect of contrast level (100% vs. 22%) under the 1FP condition to the effect of contrast level (100% vs. 22%) under the 4FP condition. The results are summarized in Table 2.

4. Discussion

The central goal of this study was to examine the impact of sensory degradation and cognitive load on task performance and electrophysiological indices of decision making and resource allocation. The study provided an experimental test of different theories about the relationship between age-related sensory and cognitive decline, which have implications for whether augmenting sensory processing might improve cognitive functioning in older adults. The major finding of the study was the interaction between task load and visual contrast level on the dependent variables of performance accuracy and the P3b amplitude (P3b-Ave and P3b-PCA), with medium effect sizes observed for accuracy and P3b-PCA, and a small effect size found for P3b-Ave. Sensory degradation and cognitive demand did not have independent, additive effects. Rather, the impact of each variable was moderated by the effect of the other, which as reviewed below, is most consistent with the information degradation hypothesis, but not the common cause or sensory deprivation hypotheses. It should be noted that the interaction between task load and visual contrast was directly linked to accuracy and resource utilization (P3 amplitude), but was not observed for speed of processing variables (RT or P3 latency). The source of this dissociation remains to be determined. Another critical finding was the interaction between task load and age group for P3b amplitude (P3b-Ave and P3b-PCA), P3 latency, and mean RT, as well as a trend towards an interaction between task load and age group for performance accuracy.

Table 2 – Effect sizes for interactions between task load and contrast level.

Variable	Cohen's d	95% CI for Cohen's d	
		Lower	Upper
Accuracy	−.49	−.91	−.05
P3b-Ave	−.31	−.68	.06
P3b-PCA	−.71	−1.2	−.22

In this study, older adults and their younger counterparts were well matched demographically. They did not differ in years of education, gender, MMSE performance, AMNART estimated IQ score, or average percentile performance on NP tests (based on age-appropriate norms). Although, indices of cognitive capacity were similar across age groups, visual processing functions (i.e., corrected VA and CS) were worse in older participants, who exhibited mild deficits.

Performance accuracy was sensitive to both visual contrast level and task load. Accuracy was lower under the most visually degraded condition (22% contrast) and decreased as a function of increasing task load. The interaction between visual contrast level and task load was due to the magnitude of the contrast level effect being greater under higher task load. Clinically, this finding suggests that as task demands increase, individuals with degraded visual processing may be more burdened than individuals with normal visual function and exhibit a disproportionate decline in performance.

Analysis of the P3b component provided an opportunity to examine mechanisms contributing to the behavioral results. There is evidence that the P3b component reflects the decision-making/categorization process or the updating activity that occurs after a decision has been made (Donchin, 1981; Donchin & Coles, 1988; Ford, 1978; Kok, 2001; Squires et al., 1973). The amplitude of the P3b indexes the resources allocated to carry out these cognitive operations or the amount of information transferred as a result of them (Johnson, 1985; Sirevaag, Kramer, Coles, & Donchin, 1989; Sutton et al., 1965; Wickens et al., 1983). We assessed P3b amplitude by analyzing both average (P3b-Ave) and temporal–spatial PCA data (P3b-PCA). Both approaches yielded an interaction between task load and visual contrast level.

For the P3b-Ave, the effect of visual contrast level (reduced P3b amplitude at lower levels of contrast) was modulated by task load. A contrast level effect was not observed under the low load condition (1FP); it only developed at higher levels of task load (2FP, 3FP, and 4FP). We suggest that more sustained attention and greater effort to manipulate the contents of WM are required to allow degraded images to be compared to the model of the target face being held in WM. There is evidence that operations involved in decision making/updating, indexed by the P3b component, and operations mediating sustained attention and the maintenance/manipulation of WM contents are derived from an overlapping pool of capacity-limited processing resources (Daffner et al., 2011; Kahneman, 1973; McEvoy, Smith, & Gevins, 1998). The interaction between task load and visual contrast level indicates that under low load conditions, ample resources are available to manage the processing of degraded images and carry out the categorization process, resulting in no decline of P3b amplitude. In contrast, under higher load conditions, there may be insufficient resources to both sustain attention for handling degraded images and execute the decision-making process, leading to the observed reduction of P3b amplitude and contributing to the decline in task performance.

The P3b-PCA also demonstrated an interaction between visual contrast and task load, although the pattern of response differed slightly from the P3b-Ave. Similar to the P3b-Ave data, under the high load condition (4FP), images presented at 100% contrast tended to elicit a larger P3b amplitude than those presented at 22% contrast. However, under the low load condition (1FP), the P3b amplitude was largest in response to the most degraded images (22% contrast). Differences in results between P3b-Ave and P3b-PCA are not surprising. Grand average ERP waveforms reflect the combination of multiple simultaneously active components that overlap in time, whereas a temporospatial PCA deconstructs the data into individual components (Dien et al., 2003; Luck & Kappenman, 2012).

Enhancement of the P3b amplitude in response to degraded images presented under low task demands has been reported previously. For example, in a study by Ford and colleagues (Ford, Pfefferbaum, Tinklenberg, & Kopell, 1982), participants were exposed to sets of either two or four digits (represented by unconnected dots). At test, half of the probes were degraded via the superimposition of eight random dots. P3b amplitude was larger in response to the degraded probes. Task load in the Ford et al. experiment was relatively low. Thus, it is not known whether, degraded stimuli presented under more cognitively demanding conditions would have elicited a smaller P3b amplitude, as was observed in our study.

The interaction between sensory and cognitive processing found in our study is not in keeping with common cause theory of cognitive aging. According to the common cause theory, the visual degradation of stimuli should not impact cognitive performance because the common source that independently causes cognitive and perceptual decline is not hypothesized to be perception (Monge & Madden, 2016). Moreover, although the sensory deprivation hypothesis predicts such an interaction, according to this theory, the interaction would not be immediately evident. Rather, a prolonged period of decline in perceptual functions is necessary for impairment of cognitive processing to develop. As such, the sensory deprivation hypothesis cannot explain the interaction between sensory and cognitive processing elicited during this brief experiment.

The study's finding of an immediately observable interaction is most consistent with the information degradation hypothesis. According to this theory, experimental manipulations of visual perception and cognitive demand should rapidly yield an interaction between these factors. Although the information degradation hypothesis posits that impaired sensory processing directly impacts cognitive function, it is possible that causality is in the opposite direction. Greater task load (or reduced cognitive capacity) may limit the availability of attentional resources to adequately process degraded visual images, leading to a decline in performance. In their review of the relationship between sensory and cognitive processes, Monge and Madden (2016) labeled this theory as the *cognitive load on perception hypothesis*. Our data provide some support for this framework. For example, consistent with the cognitive load on perception hypothesis, the magnitude of the contrast level effect for performance accuracy was much larger under at 4FP than 1FP. In addition, for the P3b amplitude, the negative impact of low contrast level only became apparent under higher load conditions.

It is important to note that the theories of cognitive aging discussed are not mutually exclusive. All may help explain changes observed with normal aging. For example, it is very plausible that common age-related physiological mechanisms (e.g., slowed transmission of information/slowed processing speed) could impair both sensory and cognitive functioning. Similarly, sensory deprivation may be associated with the long-term negative outcome of reduced engagement with the environment, which is so critical for activation and adaptation of cognitive functioning. Although our study cannot determine to what extent the changes associated with normal cognitive aging are explained by each of the theories, an interaction between the factors of sensory processing and cognitive processing substantiates the tenants of the information degradation hypothesis and the cognitive load on perception hypothesis. Regardless of the relative contribution of each factor's impact on the other, from a clinical perspective, the finding of an interaction between the two suggests that efforts to improve sensory fidelity in older adults, who are at higher risk for impaired peripheral processing, may help to conserve limited resources and improve cognitive performance.

We had expected degraded visual stimuli to have a greater impact on the cognitive processing of older adults, however, this finding was not observed. This prediction was based on the expectation of age-related declines in peripheral visual functioning (i.e., contrast sensitivity and acuity) (Jackson & Owsley, 2003; Owsley, 2011), speed of perceptual processing (Madden, 2001; Salthouse, 1996) and top-down mechanisms (Gazzaley et al., 2005; West, 1996) to compensate for the degraded bottom-up, perceptual signals. However, the magnitude of the interaction between task load and visual contrast level was not larger for older adults than their younger counterparts. The lack of modulation by age group has been reported in other studies that manipulated the visual contrast or size of stimuli (e.g., performance on a digit-cancellation test) (Laudate et al., 2012; Toner et al., 2012), which has been attributed to ceiling effects (Monge & Madden, 2016). It is plausible that in our experiment, the degree of visual degradation or the level of cognitive demand was not taxing enough for age group to have had an impact on the interaction. Moreover, the older participants in the study had relatively mild visual deficits (as measured by VA and CS) and outstanding cognitive skills (as measured by neuropsychological testing). Inclusion of a sample of older adults who have visual deficits and cognitive abilities more characteristic of this population may be necessary for the interaction between task load and visual contrast level to be modulated by age group. Additional research is needed to test these possible explanations.

Although age group did not modify the interaction between task load and contrast level, it did influence the effect of task load on the P3b amplitude, P3 latency, RT, and to a lesser extent accuracy. For both measures of P3b amplitude (P3b-Ave and P3b-PCA), higher levels of task load were associated with an increase in size only in younger adults, not their older counterparts. These findings are consistent with the CRUNCH hypothesis, which suggests that older adults reach the limits of available resources at lower levels of cognitive demand than young adults (Daffner et al., 2011; Reuter-Lorenz, 2002; Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2010). As task demand surpasses this threshold, older adults are unable to allocate additional resources to the categorization process, as indexed by a failure to increase the amplitude of the P3b component. We would anticipate that at higher levels of task load than included in this experiment, there would be a reduction of P3b amplitude, as resources are diverted to other operations such as sustaining attention or maintaining the growing contents of WM.

As with P3b amplitude, age group modified the effect of task load on P3 latency: the effect of task load was only present for young, not older adults. As task load increased, young adults displayed longer P3 peak latencies, which likely reflected the increased time needed to carry out the decision-making/updating process under these conditions. Contrary to young adults, for older adults, the P3 peak latency did not reliably change in response to task load. The study also revealed an age-related decrease in differences in P3 latency as a function of varying levels of contrast. Similarly, there was an age-associated reduction of changes in RT in response to increasing task load. Thus, for many of the dependent variables of this study (P3b amplitude, P3 latency, and RT), older participants displayed a much less differentiated response than their younger counterparts. Similar observations have been reported in other investigations of cognitive aging (Curran et al., 2001; Hahn et al., 2011; Kenemans et al., 1995; Li & Lindenberger, 1999; Looren De Jong, Kok, & Van Rooy, 1988; Lorenzo-Lopez et al., 2007; Mott et al., 2014; Park et al., 2012), which have been attributed to diminished signal-to-noise ratio in cognitive operations and decreasing processing efficiency (Li & Lindenberger, 1999).

The interaction between visual degradation and task demand, accompanied by the age-related decline in available processing resources is particularly disadvantageous to older adults. On the one hand, older individuals are more likely to demonstrate diminished CS and VA that would necessitate a greater amount of sustained attention to process degraded images. On the other hand, they have fewer resources available to manage this effort, especially as other task demands increase. Expending resources on countering the impact of sensory degradation puts older adults at risk for depleting stores that could be appropriated for cognitive processing. Developing ways to enhance the processing efficiency or capacity of older adults through programs that try to augment processing speed or WM capacity has met with limited success (Edwards et al., 2017; Rebok et al., 2014; Simon et al., 2018; Wolinsky et al., 2013). Another feasible approach is to increase efforts to optimize vision in older adults. Two of the most easily remediable visual impairments, uncorrected refractive error (URE) and cataracts, make up 75% of the total visual impairments (42% for URE and 33% for cataracts) (Lee & Mesfin, 2019). Recent investigations funded by the National Eye Institute have predicted that the number of individuals in the United States with uncorrected refractive error will double between 2015 and 2050, increasing from 8.2 million individuals to 16.4 million individuals (Varma et al., 2016).

Currently, systems for encouraging older adults to optimize their visual processing are weak. For example, Medicare, the largest insurer of health care for individuals age 65 and older (covering 97% of US elders), does not pay for vision care, which discourages or prevents many adults from enhancing their vision. Results from the current study provide additional rationale for trying to mitigate the risk of age-related cognitive decline by addressing the increase in correctable visual impairments. Empirical support for this approach was derived from a recent longitudinal investigation of the impact of cataract surgery on cognitive deterioration, which found that the rate of cognitive decline in older adults was reduced after cataract surgery and became similar to that of individuals without cataracts (Maharani et al., 2018a).

There are several important limitations to our study. First, subject numbers were relatively small, with only 32 participants across both groups (16 older adults and 16 young adults). Our small sample diminished the power of the study, for example, to find age-related differences in the interaction between contrast level and task load. Secondly, standardizing the age of all stimuli (faces) to 25 years old could have potentially introduced an “own-age bias.” As articulated by Anastasi and Rhodes (2005), individuals more readily identify faces of people that are similar in age to them, which, if true, may have disadvantaged the older participants in our study. However, Anastasi and Rhodes suggest that an own-age bias is largely weakened or eliminated when experiment instructions do not focus on the age of facial stimuli presented (e.g., asking participants to estimate the age of the individual in each photograph). In our experiment, the age of the individuals represented in the generated facial stimuli was not mentioned at any point in the study. Anastasi and Rhodes attribute the own-age bias in their study to the in-group/out-group model (IOM) introduced by Sporer (2001). Although Sporer discusses the potential threat of an age bias, the IOM is much more concerned with the potential impact of a cross-race bias. In our experiment we focused on trying to mitigate a potential cross-race/own-race bias by evenly distributing the four racial groups of the facial stimuli across all subjects. A third limitation is that during the study period, face pairs were shown in the same order. Their serial position may have been associated with primacy or recency effects. Although primacy and recency effects always may play a role when probing working memory, in our experiment having participants recognize rather than recall the stimuli (Phillips, 1983; Ward et al., 2007; Walker et al., 1993), and having an approximate 10 s interval between the study and testing periods (Kerr et al., 1999) reduce the potential impact of these factors. Importantly, primacy and recency effects were unlikely to have influenced whether an interaction between contrast level and task load was observed. An additional limitation of the study was the high educational status and estimated IQ of our subjects, which are not representative of the overall population. Moreover, the older participants only exhibited very mild deficits in visual functions, not characteristic of this age group. Although these factors may reduce the generalizability of our findings, they also highlight their potential importance. The magnitude of results found in the current study is likely to be even larger in older participants who have greater visual deficits and lower cognitive capacity. Finally, the study is limited by a ceiling effect for accuracy at the lowest level of task load. Future research should include a larger, more varied sample, and incorporate additional, more challenging levels of visual contrast and task load.

5. Conclusion

In summary, this study found an interaction between task load and visual contrast level on performance accuracy and resource utilization for the decision-making/updating process. This finding is most consistent with the tenants of the information degradation hypothesis of cognitive aging. A shared pool of resources appears to be used to mediate cognitive operations and manage the processing of degraded images. The study provides evidence that older adults reach the limits of their capacity at lower levels of task demand, consistent with the CRUNCH theory. Taken together, the results of this investigation highlight the increased vulnerability of older adults. Age-related decline in VA and CS is common, which puts older adults at risk for depleting their limited resources in the service of processing degraded visual images. More research needs to be devoted to determining the extent to which clinical interventions directed at improving vision in older adults can diminish the risk of age-associated cognitive decline.

Credit authorship contribution statement

Adam R. Billig: Software, validation, Formal analysis, Investigation, Resources, Data curation, Writing-Original Draft, Visualization.

Nicole C. Feng: Methodology, Software, Validation, Investigation, Resources, Data curation.

Hura Behforuzi: Investigation, Data curation, Writing-Review & Editing.

Brittany M. McFeeley: Investigation, Writing-Review & Editing, Project administration.

Casey M. Nicastri: Writing – Review & Editing.

Kirk R. Daffner: Conceptualization, Methodology, Validity, Resources, Writing – Original Draft, Writing-Review & Editing, Supervision, Project administration, Funding acquisition.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2020.09.005.

Open practices

All data, code, and materials used in this experiment are publicly available at https://doi.org/10.17632/cfm526zthx.1.

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