

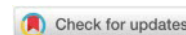
NEURAL COMPENSATION DURING INFORMATION PROCESSING IN NORMAL COGNITIVE AGING A FOCUSED TASK-BASED FMRI REVIEW

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Abstract: Normal cognitive aging is heterogeneous. Processing speed, working memory, cognitive flexibility, and executive control often decline with age. Semantic knowledge is usually better preserved. Task-based functional magnetic resonance imaging (fMRI) can show how neural recruitment changes before overt cognitive impairment. This focused review examines task-based fMRI studies in cognitively healthy middle-aged and older adults. The main domains are semantic retrieval, working memory, interference control, response inhibition, and set shifting. Evidence was identified through PubMed/MEDLINE searches through 22 July 2026, targeted searches for recent task-fMRI studies, and backward and forward citation tracking. Across domains, older adults show changes in prefrontal lateralization, earlier recruitment of dorsolateral prefrontal and frontoparietal regions, and lower segregation between control and default-mode systems. These findings do not always indicate compensation. Working-memory studies support load-dependent compensation under some conditions. Stroop, Trail Making, and cognitive-control studies also show reduced task responsiveness and dedifferentiation. Semantic tasks provide a useful contrast because core semantic regions are often preserved while control-network recruitment changes with task demand. Vascular aging is a particular constraint, because age-related changes in cerebrovascular reactivity and in the hemodynamic response can produce apparent over-recruitment in the absence of any change in neuronal computation. In line with established frameworks, compensation is treated as a task-specific and demand-sensitive fMRI change associated with preserved or better performance. Hyperactivation without behavioral benefit may reflect effort, neural inefficiency, dedifferentiation, or altered neurovascular coupling. Current evidence supports a performance-based, network-level model of compensation. Longitudinal studies, vascular calibration, standardized tasks, and better test-retest reliability are needed before task-fMRI measures can be used as individual biomarkers of successful cognitive aging.

Keywords: normal cognitive aging, neural compensation, semantic processing, task-based fMRI, cognitive control.

Field: Medical Sciences and Health

1. INTRODUCTION

Normal cognitive aging is not a uniform decline. Its course varies markedly between individuals. Processing speed, working memory, divided attention, and executive control are more vulnerable than accumulated semantic knowledge. Older adults may therefore remain clinically and neuropsychologically normal while the neural systems that support performance are already changing (Cabeza et al., 2018; Stern et al., 2019).

Here, information processing refers to the selection, maintenance, manipulation, retrieval, and control of task-relevant information. These operations are examined with paradigms that probe semantic retrieval, working memory, interference control, response inhibition, and task switching. Commonly used tests include the Stroop task and the Trail Making Test (TMT). Task-based fMRI measures BOLD responses during defined cognitive tasks and can show how regional activation and network coupling vary with task demand. Several models have been proposed to explain age-related changes in task-evoked activation and recruitment. HAROLD refers to reduced hemispheric asymmetry. PASA describes a posterior-to-anterior shift. CRUNCH proposes earlier recruitment followed by a capacity limit. STAC/STAC-r describes compensatory scaffolding influenced by reserve and life-course factors (Cabeza, 2002; Davis et al., 2008; Reuter-Lorenz & Cappell, 2008; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014). None of these patterns proves compensation by itself. Increased blood-oxygen-level-dependent (BOLD) activity can also reflect greater effort, lower neural efficiency, reduced functional specificity, or vascular effects (Morcom & Henson, 2018).

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The main question is whether additional neural recruitment helps an older person maintain performance. This review summarizes task-based fMRI findings across several information-processing domains. It applies established operational criteria for compensation and separates it from brain maintenance, dedifferentiation, and inefficient recruitment.

2. METHODS

PubMed/MEDLINE was searched through 22 July 2026. We also used targeted searches for recent task-fMRI studies, backward and forward citation tracking, and checks of primary reports in PubMed or publisher records. Search terms covered normal cognitive aging, healthy older adults, semantic processing, task-based fMRI, BOLD, compensation, cognitive control, working memory, semantic processing, Stroop, inhibition, task switching, Trail Making, processing speed, lateralization, and functional connectivity.

Eligible studies were peer-reviewed human studies of cognitively healthy middle-aged or older adults. Adult-lifespan studies were included when older-age effects could be interpreted separately. Studies had to use task-based BOLD fMRI and a defined cognitive task. We excluded resting-state-only studies, structural imaging, electrophysiology, conference abstracts, and studies limited to mild cognitive impairment, dementia, stroke, or major psychiatric disease. Seminal theoretical papers, reviews, and methodological studies were included when they directly informed the interpretation of compensation. This was a focused review. No meta-analysis or formal risk-of-bias tool was used. An fMRI finding was considered supportive of compensation only if recruitment was task-relevant, changed with cognitive demand within functional capacity, and was associated with preserved or better performance (Cabeza et al., 2018; Mauti et al., 2024).

3. RESULTS AND DISCUSSION

3.1. DEMAND-DEPENDENT PREFRONTAL RECRUITMENT

Working-memory studies show why task load matters when interpreting over-recruitment. In a verbal maintenance task, Cappell et al. (2010) found greater right dorsolateral prefrontal cortex (DLPFC) activity in older adults at lower memory loads, with similar accuracy between groups. At the highest load, older adults were less accurate and showed less DLPFC recruitment than younger adults. This pattern is consistent with the CRUNCH model. Additional resources may be recruited earlier with age, but recruitment reaches a limit when task demand exceeds available capacity. The relevant finding is the relation between activation, load, and behavior, not hyperactivation alone.

Age-related lateralization is also context-dependent. Hennessee et al. (2022) studied 461 adults aged 20-89 years. The relation between prefrontal laterality and cognition changed with age. Greater left lateralization was associated with better cognition in middle age. Less lateralized activation was associated with better cognition in older age. Bilateral recruitment may therefore be adaptive in some older adults, but it is not a universal marker of compensation. A recent task-fMRI review reached a similar conclusion. Cognitive reserve was more consistently linked to neural efficiency, while evidence for additional recruitment was mixed and more apparent at higher task demands (Mauti et al., 2024).

Eight studies are summarized in Table 1. They were selected because each links a defined task-fMRI pattern to behavior and, together, they cover the main domains reviewed here: working memory, cognitive control and set shifting, and semantic processing. The table is illustrative rather than exhaustive. It shows how similar activation patterns have been interpreted differently depending on whether a brain-behavior association was demonstrated.

Table 1. Representative task-based fMRI studies relevant to neural compensation in normal cognitive aging

Study	Task/domain	Principal task-fMRI finding	Interpretation
Cappell et al., 2010	Verbal working memory	Right DLPFC over-recruitment at lower loads; under-recruitment at the highest load	Supports load-dependent CRUNCH when performance is preserved at lower load
Talwar et al., 2020	Trail Making Test	TMT-B>A recruited left frontal-parietal/insular regions; increasing age related to lower posterior activity and worse performance	Age-related change, but not clear compensation
Rieck et al., 2021	Inhibition, shifting, working memory	Control-network connectivity became less domain-specific; frontal/default/dorsal-attention integration increased with age	More consistent with reconfiguration and dedifferentiation
Hennessee et al., 2022	Semantic judgment	Prefrontal activation became less lateralized with age; lower laterality related to better cognition in older age	Age-contingent evidence for adaptive bilateral recruitment
Wu & Hoffman, 2023	Semantic control	Core semantic responses were preserved; older adults showed altered DMN and multiple-demand engagement	Partial support; behavioral benefit not uniform
Haitas et al., 2024	Semantic distance manipulation	Task demand increased behavioral cost, but the predicted age-by-demand CRUNCH interaction was not confirmed	Does not support a universal CRUNCH response in semantic processing
Garcia et al., 2024	Semantic association	Canonical semantic regions remained robustly engaged; activation varied with association strength and abstractness	Supports maintenance/selective demand effects more than direct compensation
Langer et al., 2025	Semantic vs rhyme decisions	Semantic-network coherence increased during semantic decisions; age related to greater DMN-control coupling	Network reconfiguration; compensatory value remains inferential

Source: Compiled by the authors from the studies cited in the table

3.2. COGNITIVE CONTROL, SET SHIFTING, AND DEDIFFERENTIATION

Interference and set-shifting studies show that increased recruitment is not always beneficial. In the color-word Stroop task, Milham et al. (2002) found lower responsiveness of DLPFC and parietal control regions in older adults. Older adults also showed broader ventral visual and anterior inferior prefrontal activity and greater anterior cingulate sensitivity to competing information. The pattern was interpreted as less efficient attentional control rather than successful compensation.

The fMRI adaptation of the TMT illustrates how set-shifting demands can be examined while partly controlling for visual-motor processing through the TMT-B > TMT-A contrast. Talwar et al. (2020) studied 36 cognitively healthy adults aged 52-85 years with an fMRI version of the test. TMT performance engaged bilateral frontal, parietal, temporal, occipital, and motor regions. The TMT-B > TMT-A contrast recruited the left inferior frontal and inferior parietal regions, insula, and cingulate cortex. Older age was associated with slower and less accurate performance and lower task-related activity in posterior cortical regions. These findings describe the neural demands of set shifting in healthy aging. They do not, by themselves, show compensation.

Network analyses lead to the same caution. Rieck et al. (2021) studied inhibition, response initiation, shifting, and working memory in 144 adults aged 20-86 years. Functional-connectivity patterns across control domains became more similar with age, especially in control and default-mode systems. Frontal, default-mode, and dorsal-attention networks also became more integrated. This pattern shows age-related reconfiguration, but the loss of domain specificity also indicates dedifferentiation. Consistent with established compensation frameworks, broader integration is interpreted as adaptive only when it is associated with preserved or better performance (Cabeza et al., 2018; Stern et al., 2019).

3.3. SEMANTIC PROCESSING AND PRESERVED PERFORMANCE

Within the broader information-processing framework, semantic tasks are useful for studying compensation because conceptual knowledge is often preserved while controlled retrieval and selection become more demanding. This allows neural changes to be studied before a clear semantic deficit appears. Hoffman and Morcom (2018) found broadly similar left-lateralized semantic recruitment in younger and older adults. Older adults also showed more right frontal and parietal activity. However, greater extra-network activity was not consistently linked to better performance. Peelle et al. (2013) found greater bilateral premotor and left lateral occipital recruitment in better-performing than in poorer-performing older adults, providing a direct brain-behavior link.

Recent studies give a more detailed picture. Wu and Hoffman (2023) found preserved responses in the core semantic network, with age-related differences in default-mode and multiple-demand systems. Alves et al. (2023) found greater recruitment of temporal representational regions and medial orbitofrontal cortex when older adults named atypical concepts. This suggests greater reorganization when concepts are less prototypical. Garcia et al. (2024) found robust angular, temporal, and inferior frontal activation in healthy older adults. Activation varied with association strength and abstractness. The pattern supports demand-sensitive recruitment rather than a global age effect.

Garcia et al. (2022) found distributed task-related connectivity among anterior middle temporal, angular, and inferior frontal regions in older adults. Wu and Hoffman (2024) found stronger bilateral inferior frontal coupling during semantic tasks. In contrast, the left inferior frontal-ventral anterior temporal

interaction was stronger in younger adults. Langer et al. (2025) found increased within-semantic-network connectivity during semantic decisions and greater coupling of the default-mode network with frontoparietal and cingulo-opercular systems with age. These patterns may support performance, but a behavioral benefit was not shown in every study. Haitas et al. (2024) also did not confirm the predicted age-by-demand CRUNCH interaction when semantic distance was manipulated. Compensation during semantic processing is therefore not a uniform response to task difficulty.

3.4. WHEN DOES TASK-RELATED REORGANIZATION REPRESENT COMPENSATION?

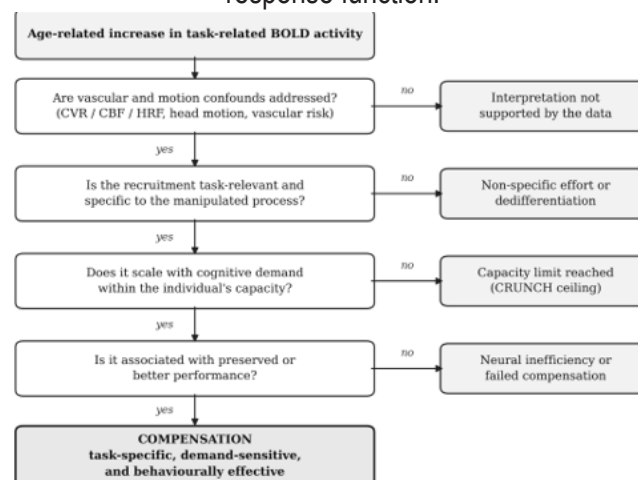
Established frameworks support three operational criteria when a task-fMRI finding is interpreted as compensatory (Cabeza et al., 2018; Stern et al., 2019).

First, the change should relate to preserved accuracy, a smaller reaction-time cost, or better performance within the older group.

Second, it should be specific to the task or to a manipulated level of demand. Diffuse hyperactivation is more consistent with nonspecific effort or lower efficiency.

Third, recruitment should occur while performance remains within the individual's functional range. Increased activation with declining performance may indicate failed compensation or resource exhaustion.

Figure 1. A decision framework for interpreting an age-related increase in task-related BOLD activity. A finding is labeled compensatory only when vascular and motion confounds have been addressed and all three criteria are satisfied. CBF, cerebral blood flow; CVR, cerebrovascular reactivity; HRF, hemodynamic response function.



Source: Authors' own elaboration

Compensation should also be separated from brain maintenance. Maintenance refers to preservation of a relatively youth-like neural pattern. Compensation requires a change in neural processing that helps sustain performance under age-related challenge. Morcom and Henson (2018) showed why this distinction matters. Standard analyses showed greater prefrontal activity with age, but multivariate analyses indicated that the extra activity carried little task-specific information. This favored reduced specificity rather than compensation. Stiernman et al. (2023) later found widespread BOLD overactivation during cognitive control in older adults without a matching increase in task-related glucose metabolism. A larger BOLD response is therefore not direct evidence of greater neuronal computation.

3.5. VASCULAR AND CARDIOMETABOLIC MODIFIERS OF THE BOLD RESPONSE

Neurovascular aging further complicates interpretation. BOLD amplitude depends on cerebral blood flow, vascular reactivity, and the hemodynamic response. In 335 adults, Tsvetanov et al. (2015) showed that vascular correction changed apparent age effects on task-related BOLD activity. Head motion, sensory impairment, vascular risk, medication, and reaction-time differences can add further bias. These factors should be measured and modeled when possible.

The vascular contribution deserves separate consideration in a clinical context, because the older adults seen in everyday practice are rarely free of cardiovascular risk. The BOLD signal is a hemodynamic proxy for neuronal activity, and the neurovascular coupling on which it depends may itself be altered by aging and by disease (D'Esposito et al., 2003). Arterial stiffening, endothelial dysfunction, reduced cerebrovascular reactivity, and cerebral small-vessel disease can all change the amplitude, shape, and

latency of the hemodynamic response function without any change in the underlying neuronal computation. Two findings discussed above point in the same direction. Vascular correction altered the apparent age effect on task-related BOLD in 335 adults (Tsvetanov et al., 2015), and widespread BOLD overactivation during cognitive control was not matched by a corresponding increase in glucose metabolism (Stiernman et al., 2023).

Vascular effects are also not uniform across the brain. In 541 middle-aged adults, cerebrovascular reactivity was lower in regions underlying the default-mode network than in comparison regions among participants with prehypertension or hypertension (Haight et al., 2015). A regionally selective vascular effect of this kind can mimic, exaggerate, or mask precisely the network-level patterns that are then interpreted as compensation or dedifferentiation. Despite this, only a small minority of the many thousands of published BOLD aging studies have applied any form of vascular correction (Tsvetanov et al., 2021). For studies of normal cognitive aging, we therefore regard it as good practice to report blood pressure, diabetes, smoking status, and white-matter hyperintensity burden among the sample characteristics and, where feasible, to acquire a vascular calibration measure such as breath-hold or hypercapnic cerebrovascular reactivity, arterial spin labeling, or resting-state fluctuation amplitude. In the absence of such information, a compensatory interpretation of hyperactivation in an older sample cannot be distinguished from a vascular one.

3.6. METHODOLOGICAL AND CLINICAL IMPLICATIONS

Most studies are cross-sectional and use different tasks and relatively modest samples. Cross-sectional differences cannot show that a compensatory pattern developed before later cognitive decline in the same person. Longitudinal studies are needed to test whether task-specific recruitment predicts preserved cognition, later decompensation, or stable individual variation. Task difficulty should be calibrated or modeled so that age groups are compared at a similar effective load. Accuracy, reaction time, and error rate can be used to quantify this load. The same nominal task may be more demanding for an older adult; without this control, hyperactivation may reflect task difficulty rather than compensation.

Reliability also limits clinical use. Elliott et al. (2020) reported poor mean test-retest reliability across common task-fMRI measures, with a meta-analytic mean intraclass correlation of 0.397. Task-fMRI remains useful for group-level research, but a single activation contrast should not be treated as an individual biomarker. A stronger candidate marker would combine preserved neuropsychological performance, reproducible task-specific recruitment, a positive brain-behavior relation, and persistence after control of vascular and motion-related confounders.

Using several paradigms may strengthen interpretation because each task stresses a different part of information processing. Semantic tasks test the interaction between stored knowledge and control. Working-memory tasks test load-dependent capacity. Stroop and response-inhibition tasks assess conflict and suppression of competing responses. TMT-B relative to TMT-A adds switching and visual-motor demands. If the same frontoparietal or cingulo-opercular recruitment appears across tasks and is linked to preserved performance, the evidence for a broader compensatory mechanism is stronger than hyperactivation in a single task.

For the practising clinician the immediate message is a cautionary one. Task-based fMRI is at present a group-level research tool. It should not be requested in order to establish whether an individual older patient is aging normally, and a single activation contrast should not be read as evidence of preserved cognition in that person. The assessment of cognition in older adults remains neuropsychological, and clinical imaging retains its established role in excluding structural, vascular, and neurodegenerative pathology. The value of the evidence reviewed here is explanatory: it shows why a seemingly more active brain in an older patient is not reassuring in itself, and why vascular health, task effort, and measured performance have to be interpreted together rather than separately.

4. LIMITATIONS OF THIS REVIEW

This was a focused rather than a systematic review. Studies were identified mainly through PubMed/MEDLINE with citation tracking, so relevant work indexed only in other databases or published in languages other than English may have been missed. No protocol was registered, study selection and data extraction were not performed in duplicate, no formal risk-of-bias instrument was applied, and no meta-analysis was undertaken; the studies in Table 1 are illustrative rather than exhaustive. The available samples are also predominantly Western, highly educated, and cross-sectional, which limits generalization to older populations with lower educational attainment or a greater burden of untreated vascular risk. These constraints should be kept in mind when weighing the conclusions below.

5. CONCLUSION

Task-based fMRI shows both preservation and reorganization during normal cognitive aging. Older adults may recruit bilateral prefrontal, frontoparietal, cingulo-opercular, and domain-specific regions as task demand rises. These changes are not always compensatory. A compensatory interpretation requires task specificity, sensitivity to demand, and a measurable behavioral benefit. Without this convergence, the finding is better described as reorganization, inefficiency, dedifferentiation, or possible failed compensation. Semantic, working-memory, Stroop, and set-shifting tasks provide complementary views of this process. Longitudinal validation, standardized behavioral criteria, vascular calibration, and better reliability are needed before task-fMRI patterns can serve as individual markers of successful cognitive aging.

Author contributions: I.S. conceived the review, performed the literature search, and drafted the manuscript. R.M. contributed to the conceptual framework, to the operational definition of compensation, and to critical revision of the neuropsychological content. H.M. contributed to the interpretation of the fMRI methodology and to the vascular and hemodynamic sections. P.A. supervised the work, contributed the clinical and cerebrovascular perspective, and critically revised the manuscript. All authors have read and approved the submitted version.

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