

REVIEW ARTICLE

Functional MRI on executive functioning in aging and dementia: A scoping review of cognitive tasks

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Abstract

Cognitive decline with aging and dementia is especially poignant with regard to the executive functioning that is necessary for activities of daily independent living. The relationship between age-related neurodegeneration in the prefrontal cortex and executive functioning has been uniquely investigated using task-phase functional magnetic resonance imaging (fMRI) to detect brain activity in response to stimuli; however, a comprehensive list of task designs that have been implemented to task-phase fMRI is absent in the literature. The purpose of this review was to recognize what methods have been used to study executive functions with aging and dementia in fMRI tasks, and to describe and categorize them. The following cognitive subdomains were emphasized: cognitive flexibility, planning and decision-making, working memory, cognitive control/inhibition, semantic processing, attention and concentration, emotional functioning, and multitasking. Over 30 different task-phase fMRI designs were found to have been implemented in the literature, all adopted from standard neuropsychological assessments. Cognitive set-shifting and decision-making tasks were particularly well studied in regard to age-related neurodegeneration, while emotional functioning and multitasking designs were found to be the least utilized. Summarizing the information on which tasks have shown the greatest usability will assist in the future design and implementation of effective fMRI experiments targeting executive functioning.

KEYWORDS

brain aging and dementia, executive function, mild cognitive impairment, neuropsychological tasks, task-phase fMRI

1 | INTRODUCTION

The process of aging involves fundamental changes over multiple domains of brain function. Though the decline of memory and sensory perception is inevitable in neurodegeneration, the most important cognitive changes with age concern those pertaining to executive function.¹ Key to the purportedly “uniquely human” actions such as advanced future planning and decision-making, executive functions critically provide the cognitive wherewithal to

suppress habitual responses in order to adapt to novel scenarios and tasks.² Unfortunately, due to their unique reliance on the prefrontal cortex (PFC; sometimes referred to as the executive control center, which is explicitly targeted by common cortical dementias such as Alzheimer's disease and progressive neuromotor diseases such as Parkinson's), these functions often deteriorate in older adults.^{3,4} Impaired executive functioning of various extents has also been associated with cerebrovascular disorders, brain neoplasms, cortical and subcortical dementias, and chronic fatigue syndrome.⁵⁻⁸ Even

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age-associated mild cognitive impairment may compromise one's attentional capacity and cognitive flexibility.⁹

Functional magnetic resonance imaging (fMRI) technology has proven invaluable in noninvasively revealing how performance in cognition can be reflected by brain activity. In particular, the discovery and subsequent research and clinical applications of blood-oxygen-level-dependent (BOLD) fMRI from 1991 onward have paved the way for applying well-designed neuropsychological tasks to investigate cognition during MRI scans.¹⁰ Most BOLD fMRI studies investigating executive function used “block design,” whereby periods of targeted functional stimulation of the brain alternate with periods of no stimulation; the difference in BOLD signal between the task phase and the resting phase (baseline) provides a robust indicator of task-relevant neural recruitment.¹¹ Alternatively, studies can make use of “event-related design” in which task conditions are discrete short-duration events of a potentially randomized order and timing, useful in reducing participant expectation bias.¹¹ A mixed block-event design may also be used. In any case, typically the task implementation in an fMRI experiment is adopted from valid neuropsychological tests on executive functioning.

Despite the large volume of work dedicated to examining executive functional change in aging and dementia through task-phase fMRI, presently no review exists in the literature to describe and catalog the relevant task protocols and the extent of their utility. Here, we conduct a broad literature search to address this gap, subdividing task designs by order of the executive cognitive domain most benefiting them as detailed below. This scoping review aims to benefit future brain research and clinical practice on aging-related changes to executive functioning using task-phase fMRI, through more effective experimental design and task selection/implementation.

2 | MAJOR DOMAINS OF EXECUTIVE FUNCTION (BY FREQUENCY STUDIED)

2.1 | Cognitive flexibility

As a critical form of cognitive control particularly relevant for the performance of novel tasks, flexibility entails the ability to distinguish between different streams of information in order to select some “appropriate” responses while inhibiting others. Critically dependent on the prefrontal cortex, this ability to adapt in novel scenarios often declines with age especially after 70.¹² Flexibility has been investigated through the use of “task-switching” or “set-shifting” experiments, in which differential feedback necessitates relearning and adjustment of one's responses.

2.2 | Planning and decision-making

Decisional capacity, particularly in emotional or risky contexts, requires the recruitment of frontal brain areas in order to sequence responses and guide behavior.¹³ A proportion of older adults may find themselves encountering difficulty with complex decisions and future planning as these cortical areas deteriorate, including the

management of their finances and other instrumental activities of daily living (IADLs).

2.3 | Working memory

It is a key form of cognition that is responsible for temporarily retaining available information for processing. Though short-term memory for one's environment and autobiographical memories may remain relatively stable with normal aging, working memory requires both the retention and manipulation of new information.¹² Assessable through methods of delayed free recall or digit span tasks, this new learning and mental restructuring is compromised as storage capacity and accuracy of recall declines. Though not explicitly searched for in this review, articles were included that connected working memory tasks to the domain of executive function specifically.

2.4 | Cognitive control

Occasionally, one's more habitual responses are not the most appropriate to the task at hand. The ability to inhibit these more automatic responses in favor of others necessitates a greater degree of preparation and recruitment of prefrontal areas.¹⁴ Age-related deterioration of these areas has been found to have a negative effect on inhibitory control and response performance, resulting in a regression to habitual responses. Assessing one's impulsivity through delayed incentive/reward tasks is one common method of determining whether cognitive control has become compromised with age.¹²

2.5 | Semantic processing

Remaining relatively stable across one's life span, the ability to understand semantic relationships and judge the meaning of stimuli based on experience relies on both prefrontal and temporoparietal regions in older adults, the areas associated with executive control.¹⁵ Additionally reliant on cognitive control to maintain and update information in working memory storage, the perseveration of semantic processing can be investigated with tasks involving word-pair relationships and verbal fluency among others.¹²

2.6 | Attention and concentration

Irrespective of one's focus of attention, the act of simply attending to a stimulus requires an increased amount of processing power the longer it must be sustained.¹⁶ Everyday behaviors such as reading or grocery shopping require prolonged periods of attention regardless of their complexity. The ability to filter out extraneous information to focus on specific stimuli, referred to as “selective attention,” provides further challenges for the aging brain and is one of the most noticeable changes to occur with age.¹² This domain can be studied using tasks requiring sustained focus or attention, including the Stroop test (a color-word interference task) and the Trail Making Test.

2.7 | Emotional functioning

Despite the relative perseveration of amygdalar function with age, the lateral PFC areas have been found to support emotional processing and their atrophy impairs emotional adaptivity.¹⁷ Age- and neurodegeneration-related compensatory neural mechanisms may compensate for lateral PFC atrophy by engaging medial instead of lateral PFC areas, especially when processing emotionally negative images or faces.

2.8 | Multitasking

The ability to partition one's attentional faculties to multiple tasks simultaneously, also known as "divided attention," is a complex executive task and declines noticeably with age where other simpler attention tasks like target counting can be preserved.¹² Additionally, the ability of older adults to learn and maintain working memory for new tasks is often compromised while having to perform another activity at the same time.

3 | METHODS

3.1 | Search terms

The literature search took advantage of the MEDLINE research database, a comprehensive worldwide collection of biomedical journals. Any non-open-access articles found therein were retrieved through the medical search engine Clinical Key by way of subscription provided by the University of British Columbia and the Fraser Health Authority.

The initial search was performed utilizing the following three sets of keywords in combination: Set 1: "aging" or "age-related" or "age-related impairment" or "age-related deficit" or "cognitive impairment" or "age-related disease" or "cerebrovascular disorder" or "stroke" or "dementing" or "mild cognitive impairment" or "MCI" or "degenerative" or "cognitive decline" or "dementia" or "vascular dementia" or "cortical dementia" or "subcortical dementia" or "frontotemporal dementia" or "frontal lobe dementia" or "Alzheimer's" or "AD" or "Parkinson's" or "Parkinsonism" or "chronic fatigue syndrome" or "brain tumor" or "brain tumour" or "frailty" or "old age"; Set 2: "fMRI" or "functional MRI" or "task based fMRI" or "task based functional magnetic resonance" or perfusion fMRI or "perfusion weighted imaging" or "PWI" or "BOLD" or "blood oxygen level dependent" or "EPI" or "echo planar imaging" or "ASL" or "arterial spin labeling"; and Set 3: "executive function" or "cognitive set-shifting" or "decision making" or "cognitive control" or "semantic decision" or "category based task" or "multitasking" or "semantic processing" or "planning." The following terms were additionally included as part of the Set 3 search string for the purpose of retrieving relevant task-phase fMRI studies that did not specify an executive function domain: "word pair" or "word matching" or "Wisconsin" or "Iowa."

The initial search retrieved 475 articles (Figure 1).

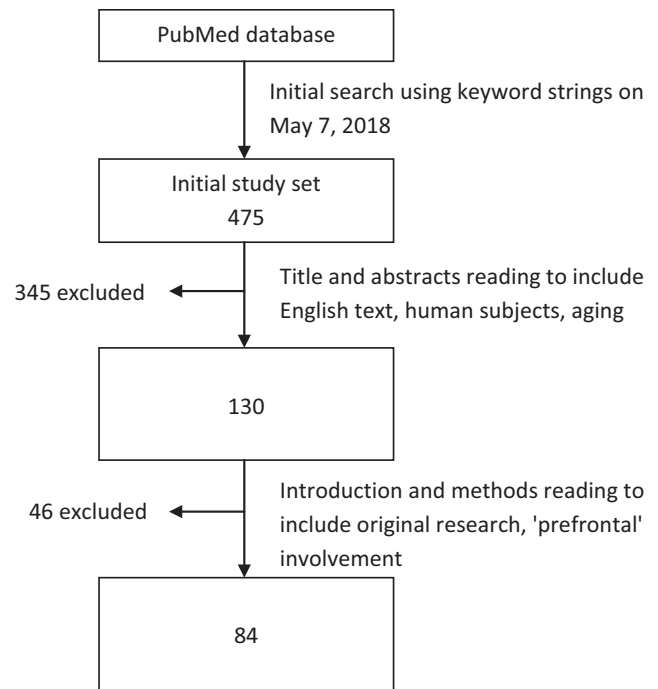


FIGURE 1 Flowchart showing the literature search process and output

3.2 | Inclusion/exclusion criteria

Title and abstract reading further restricted inclusion to English-language studies with human subjects of an older age cohort or with reference to age-related neurological diseases, producing a subset of 130 articles. From there, individual review of introduction and methods commenced for each of the articles. Reviews or meta-analyses as well as research papers utilizing only resting-state fMRI measurements were discarded. Only original research papers on task-phase fMRI studies investigating aging and age-related disease that made some mention or analysis of prefrontal areas were included. This yielded 84 remaining articles that were further reviewed and categorized by task and domain of executive function in journal articles reporting task-phase BOLD fMRI studies (Figure 1).

This review has been focused particularly on cognitive functions linked directly to the domain of executive functioning and prefrontal substrates, acknowledging their unique relationship with aging. In consequence, working memory studies were included if they were found through the "executive function" keyword (ie, original research articles using working memory tasks to investigate executive function explicitly). However, "working memory" was not included in the search string on its own, due to the fact that working memory is not confined to executive function per se but a component also of language, spatial memory, and many other cognitive domains. Similarly, verbal fluency tasks were not explicitly investigated due to their closer proximity to the domain of language, rather than executive function.

3.3 | Review and analysis

The neuropsychological battery of executive function tasks under this review followed the annals of standard neuropsychological assessment and combined with neuroimaging methods to facilitate a multidimensional approach in examining cognition. Tasks with fewer than 2 articles attributed to their use were omitted from Table 1, allowing us to focus on methods that have shown reproducibility and thus potentially greater usability. Task procedures were tallied and organized by domain of executive function (Figure 2), with individual task protocols summarized in Table 1 by order of magnitude in published research.

4 | RESULTS

Various executive functions were studied in prior research with different frequencies.

The domain of cognitive flexibility had by far the greatest volume of task-phase fMRI research in aging with 23 articles found (Table 1; Figure 2). This domain was studied particularly with regard to stimulus discrimination and the Wisconsin Card Sorting Test (WCST). Of the discrimination task procedures, three articles used a color/shape discrimination paradigm, three used a quadrant position discrimination paradigm, two used both letter and number discriminations, and one each used either letter or number discriminations alone. Of the card sorting test procedures, six articles adapted the WCST directly for their purposes; one article used an alternative to the WCST called the Montreal Card Sorting Test, and one used a similar procedure called the Dimensional Change Card Sort (Table 1; Figure 2).

The domain of planning and decision-making had the greatest variety in fMRI task designs. Though the majority of the 18 articles investigated this domain using the Iowa Gambling Task and the Tower of London task, the following designs were also used: autobiographical planning, the Game of Dice Task, lottery choice task, prediction task, the probabilistic object reversal task, and the ultimatum game (Table 1; Figure 2).

The working memory domain was investigated by 13 fMRI studies, with the great majority using the N-back or delayed match-to-sample methods of recall testing; the letter Sternberg task and distance comparisons were also used by a minor subset of studies (Table 1; Figure 2).

Eleven studies were found to have investigated the domain of cognitive control/inhibition in aging/age-related disease, particularly with regard to the antisaccade task, delay discounting, and the Simon task. However, several studies also made use of other designs including interference tasks, monetary incentive delay, and an auditory oddball paradigm (Table 1; Figure 2).

Semantic processing similarly fetched 11 task-phase articles, the majority of which explored semantic word and picture relationships in semantic classification or matching tasks. Studies also investigated how verb generation can be used to assess both recall and semantic judgment capability (Table 1; Figure 2).

Of the nine articles found devoted to attention and concentration, most made use of the Stroop color-word interference task. Those that were also implemented included the Trail Making Test, the Flanker task (involving directional judgment), and a selective attention task requiring letter discrimination (Table 1; Figure 2).

Emotional functioning and multitasking were relatively the least studied in aging/age-related disease and task-phase fMRI. The former's two articles made use of the International Affective Picture System to assess negative emotional arousal, while one article investigating multitasking used a divided attention task to assess the benefits to cognitive training in healthy older adults (Table 1; Figure 2).

Each of the following task designs was employed by only a single task-phase fMRI study, descriptions of which are not included in Table 1: selective attention (letter discrimination), interference task, auditory oddball, monetary incentive delay, divided attention task, autobiographical planning, Game of Dice Task, probabilistic object reversal, ultimatum game, prediction task, and distance comparison.^{18-29,53}

5 | DISCUSSION

In this review, we conducted a literature search to understand how changes in executive functioning commonly associated with aging and dementia have been investigated using task-phase fMRI. Our study explored eight primary executive function domains that have been most frequently and explicitly studied, as well as over 30 detailed fMRI task design implementations associated with investigating each of these domains. To the best of our knowledge, this is the first review targeting the understanding of application of fMRI tasks in testing executive function in aging and dementia. It provides useful insights to benefit future fMRI experimental design and implementation targeting various aspects of executive functioning.

Task-phase fMRI provides a powerful tool to see what happens in the brain during cognitive challenges. Among multiple brain functions that have been the target of task-phase fMRI (including sensory perception, motor, language, and memory), executive functioning stands out with unique research necessity especially in the field of brain aging and age-associated cognitive changes. As our brains mature into adulthood, we exhibit greater activation and function of task-specific prefrontal areas, associated with a myriad of executive tasks including cognitive control and flexibility.³⁰ However, executive function is also difficult to study due to the multiple domains, widespread networking with other functions involved, individual variability in expression, and the involvement of fine control and modulations. Even so, as reviewed by this article, several domains have demonstrated to be frequently under fMRI investigation with interesting findings.

Under the most studied domain of cognitive flexibility (also known as “task-switching” or “set-shifting”), stimulus discrimination and card sorting tasks were thoroughly implemented. Gold et al³¹ reported the earliest of the 10 articles on discrimination task-

TABLE 1 Task descriptions organized by executive function domain

fMRI task protocol	No. of articles pulled	Relevant domain of executive function	Description of task
Cognitive flexibility	10	Discrimination Task (letters, numbers, symbols)	Per each trial, participants are first presented with a cue (eg, a certain color, shape) or some form of written instruction informing them what discrimination task they can be expected to perform; subsequently, target stimuli consisting of letters, numbers, or symbols are presented. ^{30,31,33-38,54,55} Participants categorize the stimulus according to the relevant discrimination rule (eg, uppercase vs lowercase, blue vs red, even vs odd, top vs bottom position). As a task-switching paradigm, different trial “blocks” feature different discrimination tasks that participants must adapt to; “switching blocks” may also be included in which the discrimination tasks are switched pseudorandomly.
	8	Wisconsin Card Sorting Test (WCST)	Four deck-sized cards—one with a red rectangle, one with two green stars, one with three yellow crosses, and one with four blue circles—are presented as reference. ³⁹⁻⁴⁴ Participants must match each test card to one of the reference cards by color, shape, or number of items; feedback is given to alert them of their success or failure following each choice. Control cards are occasionally presented that identically match one of the four reference cards. After a predetermined number of consecutive “wins,” a dimensional change occurs in the matching criterion (color, shape, or number) that participants must learn and adapt to. An alternate form, the Montreal Card Sorting Test, differs in that the correct/incorrect feedback does not provide prescient knowledge to participants; the decision to include a dimensional shift after each choice is prearbitrated. ⁴⁵ The Dimensional Change Card Sort (DCCS) is another procedure that similarly requires participants to occasionally alter their sorting criteria (between color and shape), though the shapes used are three-dimensional objects including boats and animals. ⁵⁶
	5	Go/No-Go	Participants are required to perform an action given certain stimuli—for example, green → letter discrimination—and asked to inhibit that action given different stimuli—for example, white → withhold response. ^{30,57-60} Task-switching may be implemented whereby the required action for the target stimuli is varied (eg, uppercase/lowercase vs vowel-consonant discrimination).
Planning and decision-making	5	Tower of London (ToL)	Three differently colored balls are placed on three vertical rods that differ in height by one, two, and three balls, respectively. ^{4,46,47,61,62} Participants must plan to segregate balls by color cognizant that only one ball can be moved at a time, and only if there is no other ball covering it. Planning blocks (ranging from “easy” to “difficult” in terms of number of moves required) alternate with control blocks in which participants simply count balls of a certain color. Possible answers for both the planning and control tasks are presented as a binary choice.
	4	Iowa Gambling Task (IGT)	Over the course of 100 trials participants select from one of the four card decks, each draw resulting in either a gain or loss of money. ^{13,48-50} Two of the decks are disadvantageous in that they promote long-term losses (large payouts but even larger losses); the other two decks are advantageous and promote long-term gains (small payouts but even smaller losses). Feedback is provided on the amount of gain/loss following each trial. To finish with the greatest amount of money, participants must select more frequently from the latter two decks.
	4	Lottery Choice Task	During a choice phase, participants decide whether or not to gamble given the magnitude at stake and the odds of winning. ^{63,64} In a subsequent feedback phase (following an intertrial interval), they are made aware of their outcome and ultimate gain/loss should they have accepted the offer to gamble. The choice phase may consist of multiple options, some potentially prioritizing larger immediate reward with others favoring a better cumulative long-term outcome. ⁶⁵ One variant allows participants to invest a percentage of starting assets in “markets” which similarly track their gain/loss of shares. ⁶⁶

(Continues)

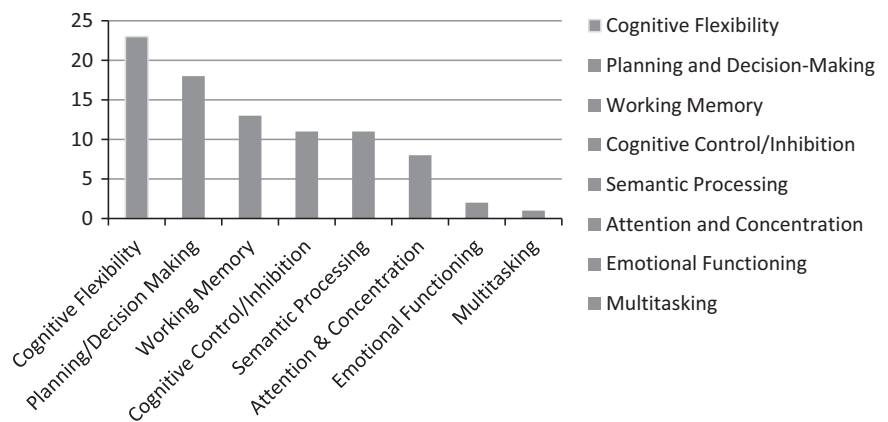
TABLE 1 (Continued)

fMRI task protocol	No. of articles pulled	Relevant domain of executive function	Description of task
Working memory	5	N-Back Task	A series of letters from the modern English alphabet are presented with preset stimulus and interstimulus intervals. ⁶⁷⁻⁷¹ Participants are tasked with button-pressing when they recognize the re-presentation of a letter consecutively (1-back) or nonconsecutively (2-back, 3-back, and so on); on the control task (0-back), they merely respond when a certain letter is displayed. Responses to each target letter are collected if the participant button-presses within a certain time interval.
	5	Delayed Match-to-Sample	Participants are shown an image (eg, scene, face, word) and asked to maintain it in mind for a fixed interstimulus period. ⁷²⁻⁷⁶ They are then asked to respond by indicating whether or not a probe stimulus matches the encoded image. Distractors may be implemented in the encoding period including “scrambled” versions of images, highly arousing/negative pictures, or neutral scenes.
	2	Letter Sternberg Task	Either 1, 3, or 6 uppercase letters are presented simultaneously on a grid for a brief period. ⁷⁷ After an interstimulus interval, participants judge whether a newly presented single lowercase letter was part of the initial study set. Variations on this task may require that participants additionally keep in mind the locations of the encoded letters, as during retrieval they must also note whether the redisplayed letter is in the exact same location as before. ⁷⁸
Cognitive control	3	Delay Discounting	Per each trial, participants are asked to choose between a fixed immediate reward option of a smaller amount or a larger, delayed amount. ⁷⁹⁻⁸¹ The latter can be varied in monetary amount and delay period.
	3	Antisaccade Task	Participants fixate on a neutral stimulus at center screen, which then changes to a colored diagram symbol indicating either a prosaccade or an antisaccade movement is required. ^{14,82,83} The target stimulus then subsequently appears at the periphery, and participants are required to either look toward or away from it based on the prior instructional cue. On baseline trials, participants are given no cues and maintain a central fixation for the entirety of the trial. A gap period may be introduced between the cue and the peripheral target in which no stimulus is shown.
	2	Simon Task	Yellow or blue squares are shown on either the peripheral left or right. ^{30,84} Participants are required to press the “left side” response key if a yellow square appears and the “right side” response key if a blue square appears, regardless of their actual position on the screen. Trials are “congruent” if the position of the colored square matches that of the response key. During control trials, the squares are presented in the center of the screen.
Semantic processing	5	Word/Picture Matching Task	Stimuli in the form of words or pictures are presented to participants to be judged on the basis of a certain semantic attribute. ^{15,26,85,86} One variation tasks participants with deciding which of a group of reference stimuli best matches with a target stimulus according to such a semantic rule. In another, the task is to decide whether a group of stimuli conform to a suggested characteristic, for example, color or shape. ⁸⁷ After a certain number of trials, the semantic classification rule may be changed.
	3	Semantic Classification Task	Semantic judgments are made by participants about familiar words or pictures when presented; for example, they may be asked to dichotomize targets into the categories “living” and “non-living.” ^{5,88,89} Some targets may be harder to classify than others and require a greater recruitment of neural resources; task blocks can accordingly be divided into the “easy” and “hard” categories.
	2	Word Generation/Verbal Fluency	In the “verb generation” task variant, participants are visually presented with a noun and asked to either generate a verb related to this noun or to simply read the noun aloud. ⁹⁰ Nouns were subdivided into “high selection” conditions (with many appropriate associated verbs) and “low selection” conditions (with fewer associated verbs). A similar paradigm known as “freelisting” tasks participants with generating as many words as they can that fit a certain semantic or phonemic category. ⁹¹

(Continues)

TABLE 1 (Continued)

fMRI task protocol	No. of articles pulled	Relevant domain of executive function	Description of task
Attention and concentration	4	Stroop Task	Names of colors are visually presented in print to participants. ⁹¹⁻⁹³ Words may appear in colors matching their namesake (“congruent” condition) or in nonmatching colors (“incongruent” condition). Classically, during active (“incongruent”) blocks, participants are required to identify the color of the ink while disregarding the meaning of the word presented. Alternatively, participants may be asked to decide whether the meaning of one word matches the printed color of another. ⁹⁴
	2	Flanker Task	Participants are shown a target arrow flanked by four other arrows and then asked to indicate the direction of the target arrow as quickly and accurately as possible. ⁹⁵ On congruent trials, the direction of the peripheral arrows matched the target, and on incongruent trials, their direction was opposite. Trials could be cued with either a small circle or a large circle, the former reducing executive function demands by helping focus visual attention. A similar procedure, the “Attentional Network Task,” requires that participants indicate the direction that the majority of four displayed arrowheads are pointing. ⁹⁶
	2	Trail Making Test	In the “A” version of the TMT, participants are required to quickly and accurately draw a continuous line connecting a series of encircled letters in sequential order. ^{91,97} In the “B” version, participants alternately connect a series of letters and numbers sequentially instead.
Emotional functioning	2	Affective Images Task	Participants are passively shown a collection of negative (unpleasant), neutral, and positive (pleasant) color images from the International Affective Picture System. ⁵² A prompt may require them to semantically classify each image to ensure attention to the task. Participants may also be asked to rate each image as to their emotional valence as above. ¹⁷

**FIGURE 2** Number of studies using task-phase fMRI in the investigation of aging and dementia, organized by domain of executive functioning

switching as pertaining to cognitive control in older adults, though the studies concerned with investigating fMRI task-switching explicitly predate this work back to the early 2000s.³² In comparing younger and older cohorts, the discrimination paradigm yielded diminished spatial extent of activation in left frontoparietal regions in older participants coinciding with a poorer performance on the task. Several other authors echoed this “switch cost” and found age-related functional decline of prefrontal cortex recruitment, while noting the tendency for older participants to compensate by relying on other neural circuits in temporoparietal regions.^{33,34} Other authors elucidated potential protective factors to cognitive flexibility with age, including cardiorespiratory fitness and bilingualism.^{35,36} Girard et

al³⁷ recently observed that estrogen therapy initiated in early post-menopause may improve prefrontal cortex recruitment in older women and buffer the age-related decline of cognitive control; in contrast, Lamar et al³⁸ found that a serotonin challenge in older women precipitated a transition to recruitment of more posterior regions.

The WCST remains one of the most commonly used neuropsychological tests for cognitive set-shifting, and 8 relevant articles were found. A well-conducted work by Monchi et al³⁹ investigated how patients with Parkinson’s disease exhibit decreased prefrontal activation following negative feedback, suggesting a connection between this deficit and the perseverative errors these patients

make when learning new card contingencies. Several authors also noted differential striatal involvement in patients with PD compared to healthy controls.^{40,41} Jubault et al⁴² found that L-DOPA treatments did little to modulate patient performance on the WCST despite increasing cortical activity in the motor cortico-striatal loop. Mild cognitive impairment has also been investigated in the context of set-shifting with the WCST.^{43,44} One of the articles used the Montreal Card Sorting Task (MCST), a variant that precludes participants from relying on feedback, to determine the role of striatal dopamine release in set-shifting for older adults.⁴⁵

The domain with the greatest variety in terms of task designs was that of planning and decision-making, with nine different paradigms including autobiographical planning, the Game of Dice Task, lottery decision-making task, prediction task, and the ultimatum game. Most extensively studied were the Tower of London (ToL) experiment and the Iowa Gambling Task (IGT), with 5 articles and 4 articles, respectively. Williams-Gray et al⁴⁶ documented the use of the ToL to investigate planning abilities in patients with PD, noting roles for the right PFC in plan construction and left dorsolateral PFC for supervision of execution. Turner & Spreng⁴⁷ suggest that poor modulation of this lateralized PFC activity in older adults may result in a failure to activate requisite neural circuits for cognitive control, hence the decline in task performance; this impairment in planning has been shown to occur early in the disease course for PD as neural activity and connectivity wane.⁴

Typically, older adults without neurological disease are not immune to impaired decision-making in risky situations either. Rogalsky et al⁴⁸ found that the ventromedial PFC, particularly critical to successful IGT performance, had greater bilateral recruitment in older adults during the task. This finding was echoed by Halfmann et al¹³ and Koestner et al⁴⁹ who added that older adults vulnerable to ill-fated purchase intentions were less able to recruit ventromedial PFC areas than those with better decision-making capacity. Other authors found task performance on the IGT was impaired in older patients with Parkinson's disease related to weakness in the prefrontal cortex.⁵⁰

For both emotional functioning and multitasking, prior research was more limited. In the former's case, this may potentially be due to the relative novelty of the International Affective Picture System and its forays into fMRI research.⁵¹ Moonen et al⁵² lament the conflicting nature of data relating to previous investigations into the "flat affect" and emotional processing deficits in patients with PD; the article opines that increased (dorso)medial PFC activity may serve to assist these patients in compensating for deficits in recognizing and modulating emotions. An age-related shift toward medial PFC activity in response to picture-induced negative emotional arousal has also been associated with compensatory methods in healthy older adults, likely due to gray matter deterioration in the lateral PFC.¹⁷

Though similar to task-switching in its necessity to maintain multiple stimulus-response itineraries in working memory, multitasking additionally requires that these be performed simultaneously. Belleville et al⁵³ used functional neuroimaging to observe how cognitive

training programs that divide attention among multiple tasks at once resulted in greater recruitment of frontal areas than individual tasks alone, suggesting that divided attentional training may uniquely buffer against cognitive decline in healthy older adults.

Our study has a number of limitations. The work has been focused on experimental designs and task implementation rather than the actual fMRI findings per se, which due to its broader scope necessitates additional research and review. In addition, the inclusion of BOLD fMRI studies only, while recent ASL studies also used tasks for dynamic CBF/CBV changes, also merits an additional review. The present study is not meant to provide a systematic review or meta-analysis. This approach precludes a more comprehensive search that could potentially better elucidate dates of emergence of each task design in the literature. In addition, result presentation was chiefly based on the quantity rather than the quality of the original studies, independent of how the fMRI tasks worked in revealing the targeted brain activation changes. Furthermore, working memory plays an important role in higher order cognition and has been widely studied, but was not included in the search string; a separate review targeting its unique relationship with aging and executive function would be apropos, given that novel executive task learning requires participants to maintain instructions in working memory storage.²

Additional limitations may be associated with the task-phase fMRI method itself. As BOLD fMRI relies on hemodynamic response, it is only an indirect measure of brain function and is highly dependent on respiratory circulation and gas exchange at the capillary level.¹⁰ Also, due to the nature of integrated brain functioning within the brain's task-related neural circuits, it can be difficult to partition domains of executive function dichotomously. Moreover, task designs must be sensitive and specific to detect a true change in brain activation reflecting task performance explicitly. Though resting-phase MRI studies were excluded from this review, future investigations could combine resting-phase network studies with task-phase fMRI so as to garner a better appreciation of the relationship between tasks and the neural substrates they purport to activate. Finally, although the results of fMRI scans may be timely and efficient, the data of clinical assessments should also be simultaneously collected for the interpretation and identification of meaningful changes in brain activity.

In conclusion, the decline of executive functioning with age and age-related disease is multifaceted and merits investigation through functional neuroimaging. Task-phase fMRI has incorporated neuropsychological assessments into studying the hallmarks of executive function, particularly with regard to cognitive flexibility and decision-making which are necessary for maintenance of independent living in older adults. Given the relative novelty of functional research into some areas of higher order cognition including emotional functioning and multitasking ability, the design and implementation of effective fMRI experiments targeting these and all other aspects of executive functioning with age is of particular importance. This needs to be realized from task selection to implementation as detailed in the present review so that proper outcomes in revealing critical brain functional changes in aging and dementia can be achieved.

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CONFLICT OF INTEREST

The authors have no conflict of interests to declare.

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