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Cognitive and gray matter volume predictors of learning across two types of casual video games in older Adults: Action vs Strategy

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ABSTRACT

Video game based and other computerized cognitive interventions are generally efficacious in bolstering cognition in adults over the age of 60, though specific efficacy varies widely by intervention methodology. Furthermore, there is reason to suspect that the process of learning complex tasks like video games is a major factor underpinning training-related transfer to cognition. The current study examined the neurocognitive predictors of learning of video games, and how those predictors may differentially relate to games of different genres. Learning rates from two different types of games, one action and another strategy, were calculated for 32 older adults (mean age = 66.29 years, 65 % Female). An extensive cognitive battery as well as structural measures of regional gray matter volumes were examined to identify the cognitive and the brain structure contributors to the learning rates for each type of game. A broad leftlateralized gray matter volume construct, as well as cognitive constructs of processing speed, episodic memory and reasoning, were found to significantly predict learning of the Strategy game, but not the Action game. Additionally, this gray matter construct was found to entirely mediate the relationships between the Strategy game learning and cognition, esp. episodic memory and reasoning. The contributions of age-sensitive cognitive skills as well as related brain volumes of lateral fronto-parietal regions to Strategy video games implicate the examined game as a potential game training tool in normal aging.

Introduction

A great deal of effort has been expended recently to investigate the efficacy of video game training in promoting improved cognitive function[64,13], owing in large part to the pervasiveness of video games as a method of entertainment coupled with their low cost and high availability[44,61]. In some studies, video game training (VGT) has been found to improve cognitive control[18,32,36,37], working memory[6,16], and even to promote neural plasticity[41,43,73], whereas other studies have demonstrated no such effect [53,56,81]. A substantial amount of this interest in the video game training field has been directed towards older adults (adults over the age of 65) with the aim to slow age-related cognitive decline. The efficacy of specific training modalities producing cognitive transfer vary widely within the older adult cohort[7,54,74], and several studies have failed to demonstrate significant cognitive effects

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from such interventions (i.e. [5,19,20,59]. Despite this heterogeneity, video game interventions been found to be generally efficacious at producing verifiable transfer in older samples[8,76].

The specific mechanisms underlying cognitive transfer resultant from video game and other cognitive intervention methods remain debated. However, both theory and experimental evidence support the cognitive demands of the learning process during the training period as determinant training-related gains in cognitive function[21,31,72]. This mechanism may also serve to explain the generally positive results of cognitive interventions in older populations despite the heterogeneity of specific methodologies and results, as a given cognitive intervention is very likely to require some level of novel task learning. From this perspective, understanding what factors influence task learning during video game or other game-like cognitive training may provide useful insight into a common method of action underlying training-related transfer across many varied studies.

Genre effects on Training-Related transfer

One major methodological variable which likely contributes to heterogeneity of effect between specific video game interventions is the varying cognitive demands of different video games[4,57,65,80]. At the coarsest level, games can be divided into genres reflecting their gameplay features, and by extension their invoked cognitive demands. Of these genres, Action video games, which emphasize quick gameplay prioritizing the identification and response to threats or situations, are the most commonly utilized games in VGT paradigms, (see [15] for a review). VGT paradigms utilizing such action games have demonstrated transfer to a wide range of cognitive constructs [34,35,33]. Strategy games, which emphasize complex problem solving and management of multiple tasks, have also been studied, though to a lesser extent (e.g. [6,32], and have been demonstrated to facilitate transfer to measures of reasoning, working memory, and cognitive[6,32,71]. Importantly, VGT studies which have directly compared Action or Strategy training have replicated this pattern of results[23,32,51,52,75]. The majority of VGT studies, and all of the above-cited direct genre comparisons, utilized healthy younger adult samples, and therefore are of limited utility in informing the design of VGT interventions in at-risk groups such as older adults.

“Casual” games – often-simpler video games designed to be played for short periods at a time – are a subcategory of video game that has received some attention in cognitive training literature[4,64,65]. While “Casual” has been examined as a genre by some past studies, games that fall into this format in fact span a wide range of game features encompassing multiple different genres[4,65]. Further, a *meta*-analytic study of the effects of specific gameplay features on training-related transfer found no meaningful difference in training outcomes between casual and non-casual games[65]. Considering this, the variety of genres represented within the “casual” game format and their shorter length makes them ideal for examining learning of different gameplay genres within a short span of time. The simplicity of casual games may make them more approachable by novice players – such as many older adults – though this reduced complexity might also negatively impact training outcomes due to lack of sufficient challenge to produce cognitive transfer.

It should also be noted that, while genre definitions often correspond to common gameplay features and associated cognitive demands, video games are becoming increasingly difficult to categorize by specific genre, and no game fully corresponds to the gameplay/cognitive demand profile communicated by a given genre label[73,80]. As such, while comparing outcomes of training with specific game genres may allow for some general conclusions, care must be made to interpret any such results with respect to the specific properties of the games examined.

Differential predictors of learning with Differing game genres

Past research from our team has examined contributors of learning novel, complex tasks and videogames generally (e.g., [11,7,68], as well as common and separable contributors of learning across game genres[4,57,66]. Basak and colleagues were able to identify both cognitive and regional gray matter predictors of older individuals learning rates on a complex working memory training task [7,68]and real-time strategy video game training[11]. However, in a series of studies on an adult lifespan sample using short-playing casual games, Basak & colleagues demonstrated both common and separable cognitive predictors[57,66], separate lifestyle predictors [66], and separable white matter tracts as predictors[57]of two genres of game learning —- Action vs Strategy. While studies investigating separable correlates of learning of different types of video games remain few in number, results from these studies suggest correlates of learning of a given game may vary with respect to the specific cognitive demand profile of that game in a way that mirrors differential effects observed from various video game interventions in elderly.

Structural correlates of game learning have been demonstrated in a handful of past studies, aside from the Ray et. al. (2017) study cited above. Erickson et al. [28] found individual differences in the volume of the nucleus accumbens to predict early learning of the Space Fortress video game in younger adults. While an interesting finding, it is limited by the study’s use of only one game for assessing complex skill acquisition – we cannot conclude that striatal volume relates to skill acquisition in *any* video game beyond Space Fortress. Additionally, analysis conducted by Erickson et al. was limited to selected regions of interest, potentially overlooking other gray matter regions that may also be predictive of video game learning. A later study by Basak, Voss, Erickson, Boot, & Kramer [11] found, using a whole-brain approach, that individual differences in gray matter volumes in several regions (pre-central gyrus, medial-frontal gyrus, dorso-lateral prefrontal cortex, anterior cingulate cortex, and cerebellum) significantly predicted learning of the game Rise of Nations (a strategy video game) in older adults. Similar to Erickson et al., the generalizability of this study is limited by the use of only one game. Interestingly, these two studies demonstrate separate gray matter correlates of the learning of an Action (Space Fortress) and Strategy game (Rise of Nations) respectively, resembling the relation between discrete white matter tracts and action/strategy learning demonstrated by Ray et. al. 2017. Naturally, as Erickson et al. [28] and Basak et al. [11] utilized different age cohorts, games andmethodologies, we cannot directly compare their results. However, there is an evident opportunity to extend the paradigm used by [57] to examine if a similar pattern of results can be found with regards to cognition, game learning, and gray matter volume.

Goals & hypotheses

The present study aims to synthesize the methodologies of the Erickson et al. [28], Basak et al. [11], and Ray et al. [57] studies to examine the common and separable cognitive and gray matter correlates of skill acquisition in different genres of video game, particularly action and strategy. Specifically, the present study intends to establish these correlates within an older adult cohort, considering the current interest in video game training as a potential cognitive intervention for older adults. Taking a cue from Baniqued et al. [4], Ray et al. [57], and Smith et al., [66], the present study utilized "casual" games in the skill acquisition paradigm, as these games will enable a greater number of repetitions of the game in a much shorter timeframe than the video games used in other studies (e.g. [11,28]. Specifically, two casual games were selected for this study, one action game (Tank Attack, Tank) and one strategy game (Sushi-Go-Round, Sushi).

We present two specific hypotheses regarding the present study. Firstly, we predict that the present study will uncover a body of common cognitive and structural correlates of learning of both the Action and Strategy games. Processing speed has been demonstrated to predict learning and performance of a wide range of cognitive tasks[3,29,38]; and as such can be expected to correlate positively with learning on both games. Similarly, both Tank and Sushi games necessitate fine control of mouse input, and as such the volume of the motor areas are expected to be common correlates of game learning rate. Both Sushi and Tank games are complex tasks; therefore, measures of higher-order cognitive processes such as working memory and executive control– and the volume of associated gray matter areas – may prove to be common correlates of both games. Areas we expect to be associated with these higher-order cognitive tasks include the lateral and medial prefrontal cortex and inferior parietal sulcus, due to their known association with working memory[53,62], as well as the superior and middle frontal gyri and inferior parietal lobule, as the volume of these regions have been implicated in executive control processing[28,82,83]. However, while both games are complex tasks, Sushi is considerably more complex than Tank in terms of the number of simultaneous factors that must be monitored to succeed at the game, and as such these higher-order cognitive processes may alternatively prove to be selective correlates favoring the strategy game.

Secondly, we hypothesize that, in addition to common correlates, the present study will demonstrate separable correlates of action and strategy game skill acquisition. As mentioned above, working memory and executive control, as well as the volume of associated gray matter areas, may prove to be specific predictors of Sushi learning, due to the difference in relative complexity between that game and Tank. Additionally, measures of long term memory as well as the gray matter volume of the hippocampus and basal ganglia are expected to selectively correlate with Sushi, as that game necessitates the memorization and recall of specific sushi recipes, necessitating episodic memory recall. Tank Attack places emphasis on the rapid identification and targeting of threats, and as such places unique demand on perceptual faculties. As such, measures of perception, as well as the gray matter volumes of regions in the dorsal and ventral attention streams are likely to be selective correlates of learning of that game. The current study intends to address both of these hypotheses via a correlational analysis comparing individual learning rates for the selected action and strategy games, a comprehensive cognitive battery, and measures of regional gray matter volume gleaned from MRI analysis.

Methods

Participants

Inclusion criteria included: 60 years of age or older, a minimum of a high school education, Mini Mental State Exam (MMSE; [30]) of 24 or greater, right-handedness, and corrected vision of 20/30 or better. Exclusion criteria included: color blindness, Instrumental Activities of Daily Living (IADL,[42] assessment score ≤ 3), Geriatric Depression Scale (GDS,[63] score ≥ 5), involvement in cognitive training, a history of psychiatric disorder, illness or trauma affecting central nervous system, substance/alcohol abuse, use of psychotropic medication, untreated hypertension, metallic implants, large tattoos, and claustrophobia. To account for potential familiarity effects, participants who reported playing more than five hours of video games per week, and participants who reported familiarity with either of the two casual games utilized in this intervention (see below) were also excluded.

Forty four community-dwelling older adults who live independently were recruited through advertisements; only 33 attended all sessions of this study. Schedule conflicts, MRI computability, and transportation issues accounted for all incidents of dropout in the sample. One participant was excluded from the analysis due to excessive motion during the acquisition of the MRI scan. One further participant reported playing video games for more than 5 h per week on average and was excluded, resulting in a final sample of 31 participants ($M_{age} = 66.29$ years, $SD_{age} = 6.6$ years, 65 % Female). Of these remaining participants, 28/31 reported zero hours of habitual video game play, and 3/31 reported playing an average of one hour or less per week.

Design

This study consisted of 4 sessions. The first session included a 45 min screening session in which all inclusion and exclusion criteria described in section 2.1 above were assessed. Subjects then filled out a detailed game-experience questionnaire and demographic questionnaire, before completing and a 75 min video game learning session on one of the two selected casual games (see below). In session 2, participants underwent another 75-min video game learning session on the other game, and 75-min cognitive testing session, in which all cognitive assessments listed in section 2.2.2 were administered. The order of games was randomly counterbalanced across these first two sessions. In session 3, participants experienced a mock scanner to ensure participant's eligibility to undergo an MRI session. In Session 4, structural MRI scans were collected. Ample opportunities for breaks were provided across all game and cognitive testing sessions to insulate against cognitive fatigue. The second and third sessions occurred within a week of the previous session for all participants, and the fourth session occurred within two weeks of the third session for all participants. No assessments were repeated across any of the four sessions.

Casual games

Two casual games were selected from a website that has been used in prior research[4,57] (miniclip.com). One game, Tank Attack (Tank), is an action game, whereas the other, Sushi Go-Around (Sushi), is a puzzle/strategy game. These games were chosen because a) a single instance of the game can be completed in a short amount of time ($\sim$6 min for Sushi and $\sim$ 5.5 min for Tank), b) they have an adaptive difficulty level that increases as the player performs better (5 increasingly difficult “missions” for Tank, 7 increasingly difficult “days” for Sushi), and c) because they were readily and freely available online at the time of data collection.

Tank Attack, an action game, involves detection and destruction of enemies. Tank Attack also involves switching between movement and attack modes of the controlled tank. Sushi Go-Round is a restaurant simulation game which puts demands on multi-tasking (e.g., cleaning plates, serving sushi, ordering supplies), spatial memory (e.g., which customer came first), emotional motoring (e.g., customer happiness), and memory (e.g., remembering recipes for faster sushi preparation, increase in recipes), and can be considered a strategy game. Both games yield final game scores, wins/losses, and levels reached. Image captures from these games are depicted in Fig. 1.

Participants played, on average, 16 ± 3 sessions of each game ($M_{sessions} = 15.79$, $SD_{sessions} = 2.77$). This variability in games played is due to variation in the proportion of rest time taken by each participants (participants who rested more in the 2-hour testing window played fewer sessions), as well as variability in the win ratio between participants (in each game, failure results in the early termination of a session, hence participants who failed sessions more often played shorter sessions on average, and therefore played more sessions in the 2-hour testing window). Screen recordings of each participants’ gameplay was manually coded for both final output score for each game played and the number of instances taken to reach highest performance (score output) in each game. Score outputs for both games are depicted in Fig. 2. Learning rates were calculated for each participant by fitting logarithmic functions to the standardized score output of each respective game (higher scores indicate higher success in game play performance; [11,17,57,66,68].

Cognitive battery

Table 1 provides a summary and references of the cognitive tasks that constitute the cognitive battery. Wherever possible, tasks were selected using a construct approach, with two or more tasks assessing the same cognitive function. Constructs represented in Table 1 included cognitive control (6 tasks), working memory span (3 tasks), episodic memory (5 measures across 3 tasks), perceptual discrimination (3 tasks), and processing speed (4 tasks). A construct approach incorporating multiple measures of individual cognitive abilities was taken avoid the single-task impurity problem [48,49]. Additionally, single measures of both reasoning and general cognitive functioning were included in this battery.

Structural Magnetic Resonance Imaging (MRI) methodology

A Philips Achieva 3 T MR scanner (Philips Medical Systems, Andover, MA) equipped with a 32-channel head coil was used to acquire T1-weighted anatomical images (TR = 8.1 ms; TE = 3.7 ms; flip angle = 12°; 22 cm field of view; 256 × 204 matrix; 1 mm3 voxels; 160 slices, sagittal acquisition). Cortical reconstruction and volumetric segmentation of these images was then performed [87] with the Freesurfer 6.0 image analysis suite, which is documented and freely available online (http://surfer.nmr.mgh.harvard.edu/). The technical details of these procedures are described in our prior publications, such as [11,88]. The gray matter volumes of the resulting segmentations were utilized as the structural data of interest in subsequent analyses.

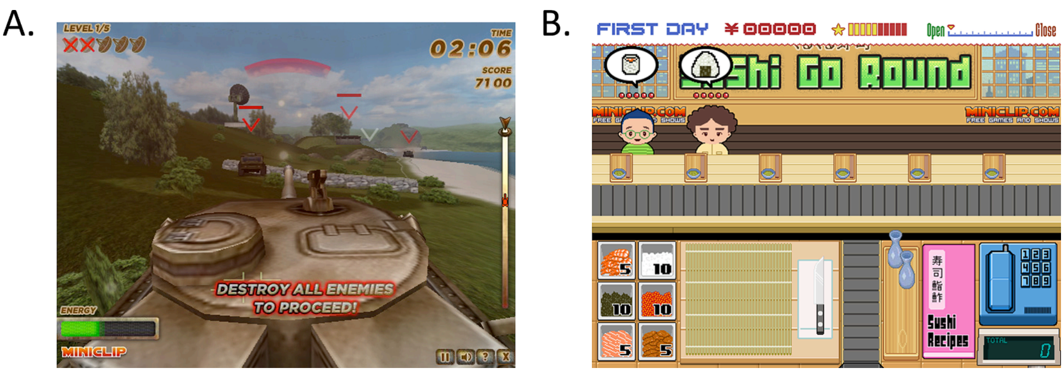


Fig. 1. *Training games utilized.* Panel A depicts a scene from the Action game (“Tank Attack 3D”). Panel B depicts a scene from the Strategy game (“Sushi-Go-Round”).

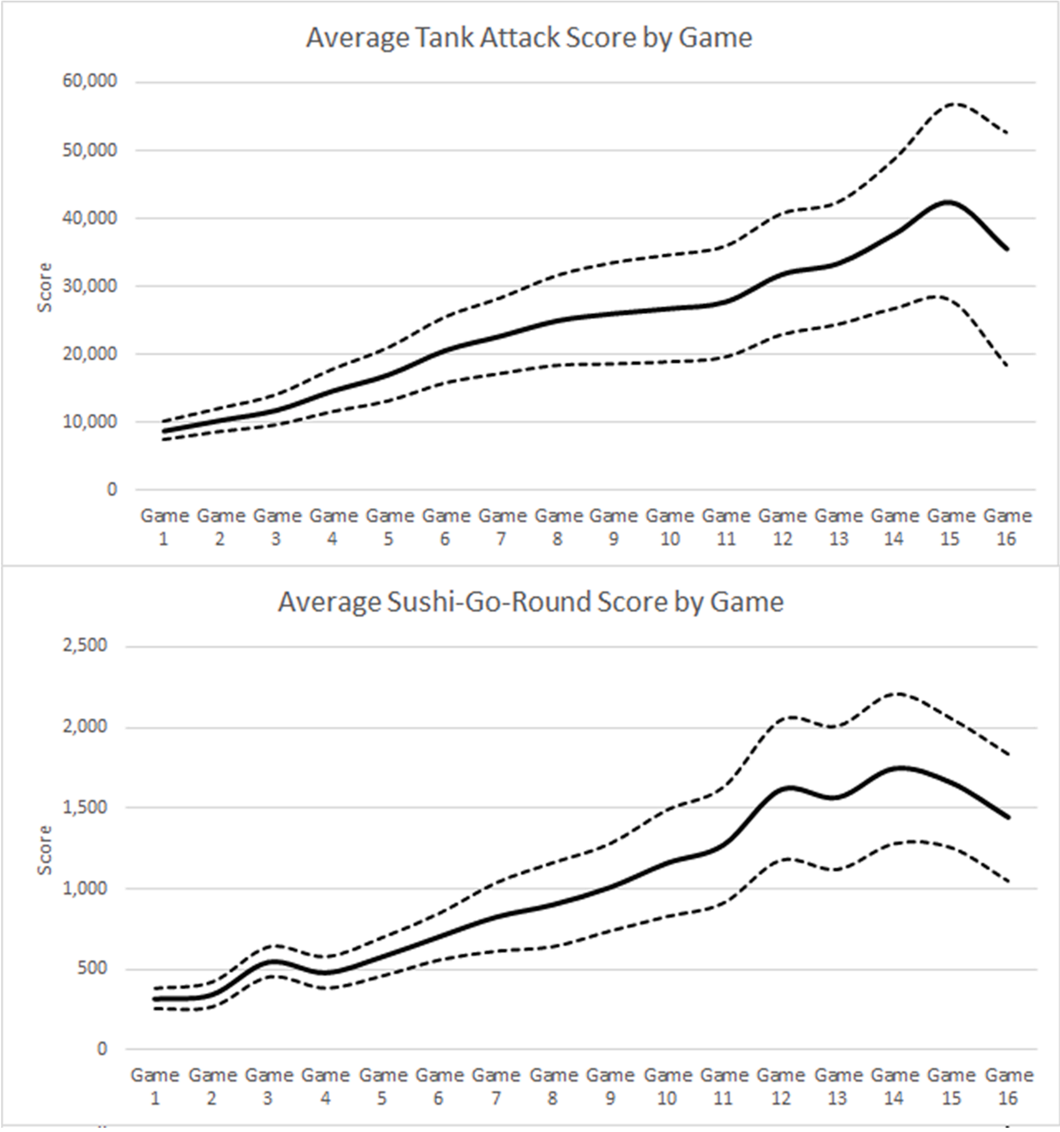


Fig. 2. *Score output for Sushi and Tank, plotted by game.* Due to variability in the total number of games played by each participant, only scores for the average number of games played (i.e., 16) across all participants are plotted. Note that the score values given are the raw score outputs from each game, and hence are not directly comparable in terms of scale.

Multiple Factor Analysis (MFA)

The numerous assessments in the cognitive battery collectively constituted the *Cognitive data* of this experiment. The *Structural data* of this experiment consisted of all discrete cortical regions parcellated by the Freesurfur algorithm, as well as selected subcortical and medial temporal regions (hippocampus, amygdala, parahippocampal gyrus, thalamus, caudate, and putamen). These gray matter regions were selected based on a priori hypothesis regarding the cognitive processes expected to be invoked by the selected Action and Strategy games, and the gray matter regions that subserve those cognitive processes. The learning rates of both Sushi and Tank constituted the *Game data* of this experiment.

Due to the large number of variables, particularly those pertaining to structural brain regions of interest (ROIs), a multiple-factor analysis (MFA[1]) of the data was performed initially to determine the most relevant measures for further analysis, with the *Cognitive*, *Structural* and *Game data,* each constituting a separate table in this MFA. This analysis was conducted using the MExPosition package in R[12]. Significance of revealed components of variance was established via a 1000-iteration permutation test[14]. Significant contributors to each revealed component of variance were identified via a 1000-iteration Bootstrap test performed on the contributors to each component[27,39], with contributors demonstrating a bootstrap ratio >= 2 considered significant. These inferential analyses were conducted using the InPosition package in R[12]. Prior to performing the MFA analysis, age was co-varied from the cognitive data

Table 1
Summary of cognitive tasks.

Cognitive Task	*Primary Construct*	*Secondary Construct*	*Reference*
Task Switching – HLOE	Cognitive Control	Processing Speed	Basak et al. [6]
Task Switching – CVOE	Cognitive Control	Processing Speed	ELSMEM [84]
Unpredictable 2-Back	Cognitive Control		Basak & Verhaeghen [10]
Visual N-Back Task	Cognitive Control		Original task modified from Verhaeghen & Basak [85].
Computation Span	Working Memory Span		ELSMEM [84]
Reading Span	Working Memory Span		ELSMEM [84]
Backwards Span	Working Memory Span		Wechsler [77]
Forward Span	Immediate Episodic Memory		Wechsler [77]
Story Memory	Immediate Episodic Memory		Stern, Sano, Paulsen, & Mayeux [78]
Selective Reminding Task	Immediate and Delayed Episodic Memory		Buschke & Fuld [22]
Simon Task	Cognitive Control	Perceptual Discrimination	ELSMEM [84]
Flanker Task	Cognitive Control	Perceptual Discrimination	ELSMEM[84]
Trail-Making Task B	Cognitive Control		Reitan [60]
Trail-Making Task A	Processing Speed		Reitan [60]
Digit-Symbol Substitution Task	Processing Speed		Stern, Sano, Paulsen, & Mayeux [78]
Enumeration Task	Perceptual Discrimination	Cognitive Control	Basak & Verhaeghen [86]
Ravens Progressive Matrices (RAPM)	Reasoning		Ravens [79]
MMSE-2	General Cognitive Functioning		Stern, Sano, Paulsen, & Mayeux [78]

table, as age within an older adult cohort can influence performance on many of the tasks used in the cognitive battery[90]. Similarly, the structural data were corrected for both age and estimated intracranial volume (eICV), as age is known to be negatively correlated with many gray matter regions within the older adult age group[58], and eICV may be collinear to any volumetric measure[89].

Results

Results from Multiple Factor Analysis (MFA)

The MFA revealed a total of 36 components of variance in the pooled *Cognitive, Structural,* and *Game data*. Three of these components, accounting for a total 19.02 % of the total variance in the sample, were demonstrated to be significant via the permutation tests. A visualization and summary statistics for these significant components can be found in the supplementary material for this manuscript (Figure S1 and Table S1). This relatively low proportion of the explained variance suggests that our data are strongly influenced by nonsystematic variance, which is not surprising considering the shallow nature of the data examined (relatively few subjects coupled with many observations per subject). The first of the three significant components identified in this analysis – accounting for 42.58 % of the explained variance of the sample and of 8.1 % of the total sample variance – included structural gray matter and cognitive contributors, as well as learning rate contributors from both games, which implicate it as potentially relevant to the experimental questions we sought to answer in the present study. A summary of the significant contributors to component 1 can be found in Supplementary Table S2. The second and third of these three significant components included only cognitive and structural contributors, but did not include any game variables. These components are therefore not relevant to the core goal of understanding the three-way Game-Structure-Cognition relationship, and were not analyzed further. These results suggest that, among the subset of variance that the multiple factor analysis was able to explain, a single factor of shared variance between the *Cognitive, Structural,* and *Game* data was most explanatory of the pattern of relationships between variables in the combined dataset. Considering these results, we designed our subsequent analyses around those measures which were found to significantly contribute to this primary component identified by this MFA, as that component included significant contributors from all the three datasets of interest (*Game, Cognition and Structure*) allowing for understanding of the three-way relationship.

Separate and common correlates of game learning rates: cognitive constructs and gray matter volume

Episodic memory (EM), cognitive control (CC), working memory span (WMS) and processing speed (PS) constructs were created from significant cognitive contributors to the first component of variance revealed by the MFA (described in supplementary Table S2). Constructs were calculated by standardizing (z-scoring) and averaging measures found to significantly contribute to the first component of variance, with equal weight assigned to each measure. An index of which measures were assigned to which cognitive construct, and a description of each measure, can be found in supplementary Table S3 and S4. Additionally, single measures of perception (Per), and reasoning (Rs), which significantly contributed to the first component of variance, were standardized and retained for subsequent analysis. All significant gray matter volume contributors to the first component of variance were standardized (z-scored) and averaged to create an overall measure of gray matter volume (GM Construct). A visualization of the gray matter volumes included in the GM Construct can be found in Fig. 3.

A cross-correlation of these cognitive constructs, the GM construct, and learning rates on both the Strategy and Action games was conducted to assess first-order relationships between these variables. These correlations controlled for both Age and eICV. Resulting partial correlations are shown in Fig. 4. Learning rate from the action game (Tank) was not found to be correlated with the GM construct, $r(27) = 0.21, p = 0.27$, nor with any of the cognitive constructs or measures[PS, $r(27) = 0.18, p = 0.35$; CC, $r(27) < 0.01, p = 0.98$; WM, $r(27) = 0.12, p = 0.54$; EM, $r(27) = 0.23, p = 0.24$; Perception, $r(27) = -0.25, p = 0.19$; Reasoning, $r(27) = 0.18, p = 0.53$]. Learning rate on the strategy game (Sushi) was significantly correlated with the GM construct, $r(27) = 0.65, p < 0.001$, as well as the PS construct, $r(27) = 0.53$, $p = 0.003$, EM construct, $r(27) = 46$, $p = 0.01$, and Reasoning measure, $r(27) = 0.48$, $p = 0.01$. Strategy learning was not found to be significantly related to the CC construct $r(27) = -0.14, p = 0.48$, WM construct, $r(27) = 0.24, p = 0.21$, or the Perception measure, $r(27) = -0.19, p = 0.32$. These results demonstrate a strong relationship between participant's learning rate on the Strategy video game and measures of gray matter volume, processing speed, episodic memory, and reasoning. Action game learning demonstrated no such relationship in our sample.

Gray matter volume as a mediator of the cognition-learning predictive relationship

The above analysis demonstrated an intercorrelation between Strategy game learning, gray matter volume, and several cognitive constructs. To further examine these relationships, we next conducted a series a mediation analyses to assess the possible mediating effect of the GM construct on directional cognition learning relationships where cognition predicts game learning. We restricted our analyses to those relationships which were possible considering the correlational results already observed between cognition-learning, thus restricting our analyses to EM → Strategy Game Learning (SGL), PS → SGL, and Rs (reasoning) → SGL.

Each mediation analysis was achieved as a series of multiple regressions. First, direct paths between each cognitive construct (EM, PS, Rs) and the GM construct were calculated via two-step regressions, with eICV entered as a control variable in step 1, and the cognitive construct of interest entered in step 2. Direct paths between each cognitive construct (EM, PS, Rs) and SGL were then calculated in the same way, again controlling for eICV. Indirect path values were calculated via a 3-step regression, with eICV entered in step 1, the GM construct entered in step 2, and the cognitive construct/measure of interest entered in step 3. Lastly, indirect path beta values were calculated using the Product of Coefficients method[69], and verified using the Difference of Coefficients method [40], which produced identical results[45].

The EM → Sushi Game Learning (SGL) predictive relationship was found to be completely mediated by the GM construct (EM → SGL $\beta = 0.5, p = 0.008$; adjusted EM → SGL $\beta = 0.09, p = 0.62$; indirect path $\beta = 0.27$), as was the Rs → SGL predictive relationship (Rs → SGL $\beta = 0.52$, $p = 0.004$; adjusted Rs → SGL $\beta = 0.21$, $p = 0.21$; indirect path $\beta = 0.31$). Conversely, the PS → SGL predictive relationship was not found to be mediated by the GM construct (PS → SGL $\beta = 0.56, p = 0.005$; adjusted PS → SGL $\beta = 0.21, p = 0.001$; indirect path $\beta = 0.05$). As the PS → GM directional relationship was found to be non-significant after controlling for eICV, $\beta = 0.31, p = 0.47$, we can conclude that these two measures (PS and GM) are independent predictors of Strategy Game Learning (SGL). Model summaries of all regressions conducted as part of this mediation analysis are presented in Table 2, and the direct and indirect path relations are visualized in Fig. 5.

Regional gray matter volumes mediating cognition-learning predictive relationship

The above results demonstrate that the GM construct strongly mediates the EM → SGL and Rs → SGL relationships. However, that GM construct constitutes a wide area of neural matter, which limits the conclusions we can make based on those findings. To further investigate this relationship, we next separated this construct into its 21 constituent regions of interest (ROIs), with the intention of determining which, if any, of these regions are the primary mediators of the EM → SGL and PS → SGL relationships. To test this, we reexamined the indirect cognition → SGL pathways via multiple regression analysis, substituting the individual GM regions for the GM

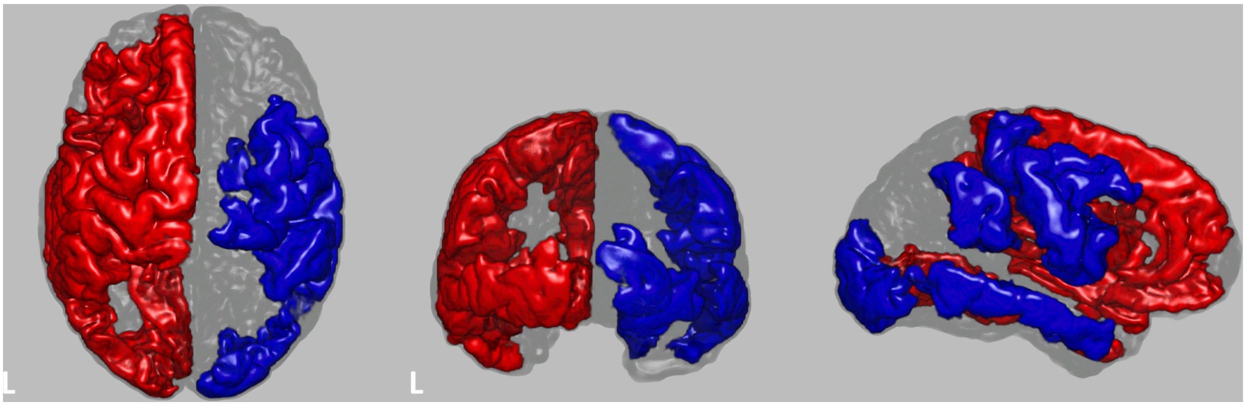
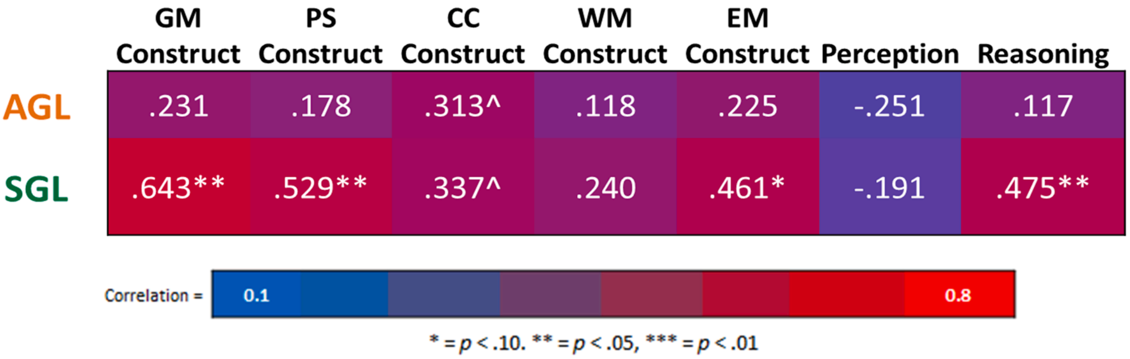


Fig. 3. Depiction of Gray Matter volume construct. Volumes are colorized by hemisphere (left = red).



	GM Construct	PS Construct	CC Construct	WM Construct	EM Construct	Perception	Reasoning
AGL	.231	.178	.313^	.118	.225	-.251	.117
SGL	.643**	.529**	.337^	.240	.461*	-.191	.475**

Fig. 4. Heat-map of partial correlations between the two types of game learning and constructs (cognitive and structural). Correlations are corrected for eICV and age.

Table 2
Model fit for all regression models conducted as part of the mediation analysis.

	Regression	*Step*	*Variable Added*	R^2	ΔR^2	p-value
A	*EM → GM*	1	eICV	**0.49**	–	**<.001**
		2	EM Construct	**0.68**	**0.19**	**<.001**
	PS → GM	1	eICV	**0.49**	–	**<.001**
		2	PS Construct	**0.5**	0.05	0.466
	Rs → GM	1	eICV	**0.49**	–	**<.001**
		2	RAPM	**0.63**	**0.14**	**.002**
B	*EM → SGL direct*	1	eICV	0<.01	–	0.77
		2	EM Construct	**0.48**	**0.48**	**0.008**
	PS → SGL direct	1	eICV	0<.01	–	0.77
		2	PS Construct	**0.31**	**0.31**	**0.001**
	Rs → SGL direct	1	eICV	0<.01	–	0.77
		2	Rs	**0.27**	**0.27**	**0.004**
C	*EM → SGL indirect*	1	eICV	0<.01	–	0.77
		2	Gray Matter Construct	**0.47**	**0.47**	**<.001**
		3	EM Construct	**0.48**	0.01	0.62
	PS → SGL indirect	1	eICV	0<.01	–	0.77
		2	Gray Matter Construct	**0.47**	**0.47**	**<.001**
		3	PS Construct	**0.69**	**0.22**	**<.001**
	Rs → SGL indirect	1	eICV	0<.01	–	0.77
		2	Gray Matter Construct	**0.47**	**0.47**	**<.001**
		3	Rs	**0.5**	0.03	0.212

Note. Section A reports regression testing the direct cognition → GM relationships. Section B reports regressions testing the direct cognition → SGL relationships. Section C depicts regressions testing the indirect cognition → SGL relationship, accounting for GM. *p-value* represents the significance of the predictor variable added in the step-wise regression model, and is related to the change in *R*-square. Rs (reasoning) is measured by RAPM reasoning task.

construct. As before, eICV was entered in step 1 as a control variable. The cognitive variable of interest (EM/Rs) was entered in step two. Step three consisted of automated stepwise entry of all 21 GM regions into the model using a $p = 0.05$ cutoff criteria. Model summaries of these regressions are presented in Table 3, section A. These regression implicated two discrete gray matter regions as potential mediators of the EM → SGL relationship (the left lateral occipital cortex, and left caudal-middle-frontal gyrus), and three regions as potential mediators of the Rs → SGL relationship (the right caudal-middle-frontal gyrus, left pars orbitalis, and right middle temporal lobe). We then assessed the direct relationships between EM/Rs and those gray matter volumes implicated as potential mediators via two-step regressions, with eICV entered in step 1 and the cognitive variable of interest entered in step 2. Model summaries for these regressions can be found in Table 3, section B.

Combining the results of these regressions with those conducted to test the direct cognition → SGL relationships in our earlier analysis allowed us to determine if these specific gray matter regions mediate the observed relationships. As with our previous analysis, indirect pathway betas for these analyses calculated using the Product of Coefficients method[69], and verified using the Difference of Coefficients method[40], which produce identical results[45]. The EM → SGL relationship was found to be partially mediated by the volume of the left lateral occipital lobe and left caudal-middle-frontal gyrus (EM → SGL $\beta = 0.5$, $p = 0.008$; adjusted EM → SGL $\beta = 0.26$, $p = 0.01$; indirect path $\beta = 0.35$). However, the EM construct was not found to be a significant predictor of left lateral occipital volume after controlling for eICV, $\beta = 0.15$, $p = 0.22$, indicating that this partial mediation is driven by the volume of the left caudal MFG. Conversely, no specific regional mediators were identified in the Rs → SGL relationship (Rs → SGL $\beta = 0.52$, $p = 0.004$; adjusted EM → SGL $\beta = 0.61$, $p < 0.001$; indirect path $\beta = -0.09$). These mediation analyses are visualized in Fig. 6.

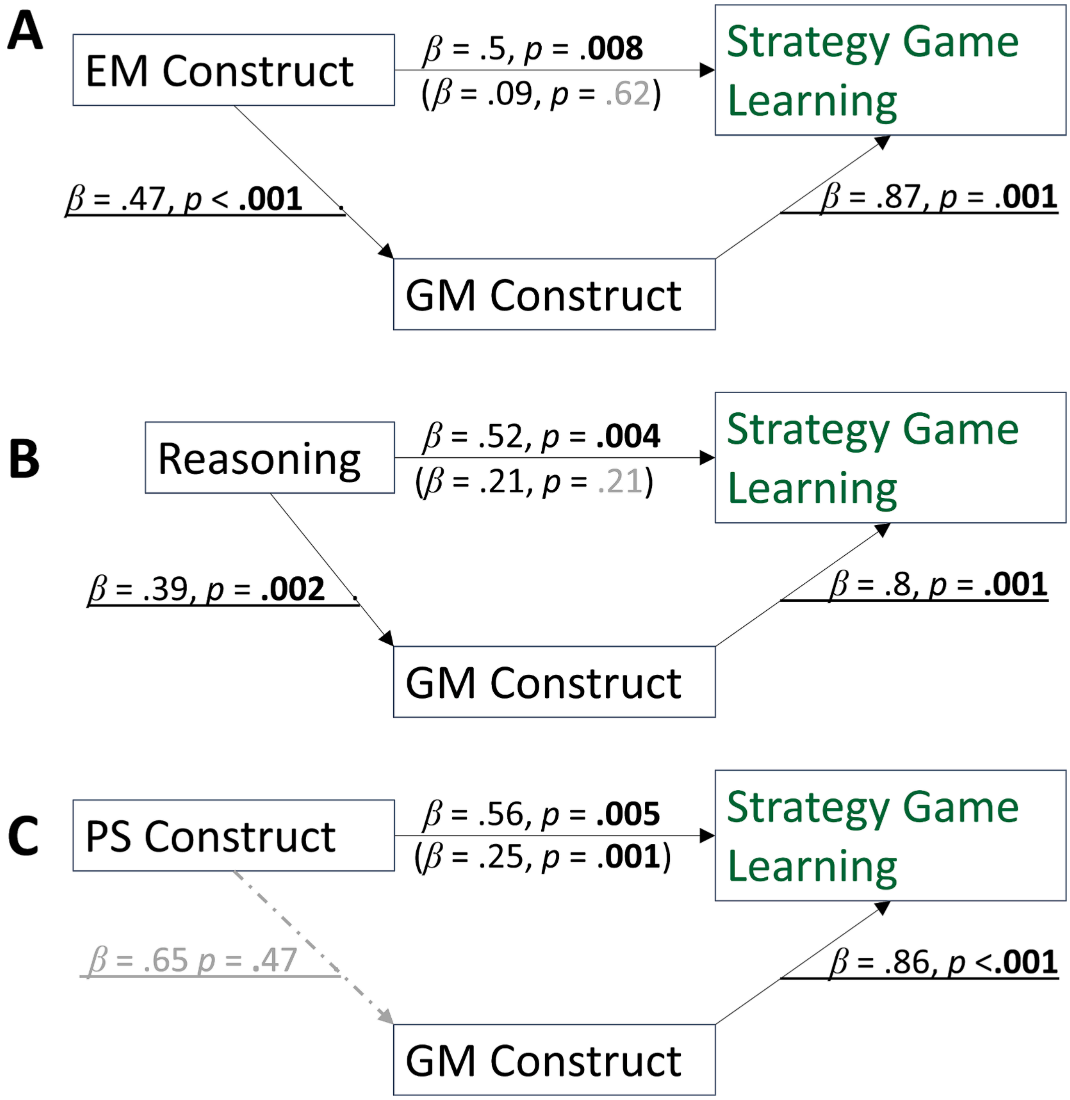


Fig. 5. *Diagrams of Construct Mediations.* Standardized Beta and significance values are given for all depicted relationships. Parenthetical values reflect the direct cognition to game learning pathway after the indirect pathway via the GM construct has been taken into account. Panel A depicts the episodic memory construct to strategy game learning relationship. Panel B depicts the reasoning construct to strategy game learning relationship. Panel C depicts the processing speed construct to strategy game learning relationship. “Reasoning” refers to the Ravens Progressive Matrices/RAPM task.

Discussion

Contrary to our hypotheses, we did not identify common cognitive/structural correlates of learning on the two examined casual video games, nor did we identify correlates specific to learning of the examined Action video game. This is due to the fact that, at a base level, learning of the examined action game (Tank Attack) was not related to the cognitive and brain structure variables examined in this study. This is likely due to specific properties of the action game examined rather than a true indication that learning of these games is not related to cognitive ability or regional gray matter volumes – as reviewed above, such factors have shown to be related to performance and learning on various action games in the past[28,57]. It is also worth considering that Action games are a strongly heterogeneous genre of video games[4]; Dale & Green, 2017; [65], and any number of factors that distinguish Tank Attack from other similar games could result in a different pattern of relationships with the neurocognitive correlates of learning examined in this study.

One such factor is the relative complexity of Tank Attack as a game – Tank Attack belongs to the “Rail Shooter” subgenre of First/Third person shooters which have been commonly studied in the Action game literature[64,65]. This subgenre of shooter differs from its parent genre in that the player does not have direct control of their movement, being limited to a specific, predetermined path through the environment. This removes the element of spatial navigation and exploration from such “Rail shooters”, and thereby greatly limits the strategies with which the player can engage with the game. As noted in our introduction, Tank Attack is slightly

Table 3
Results of regression analysis on the three observed mediations after separating the GM Component into its constituent gray matter volumes.

	Regression	*Step*	*Variable Added*	*R^2*	*ΔR^2*	*p*
A	*EM → SGL indirect*	1	eICV	0<.01	–	0.77
		2	EM Construct	**0.23**	**0.23**	**0.008**
		3	Left Lateral Occipital Gyrus	**0.43**	**0.2**	**0.004**
		4	L Caudal Middle Frontal Gyrus	**0.56**	**0.13**	**0.013**
	Rs → SGL indirect	1	eICV	0<.01	–	0.77
		2	Rs	**0.27**	**0.27**	**0.004**
		3	R Caudal Middle Frontal Gyrus	**0.51**	**0.24**	**<0.001**
		4	L Pars Orbitalis	**0.59**	**0.08**	**0.034**
		5	R Middle Temporal Gyrus	**0.66**	**0.07**	**0.032**
B	*EM → Left Lateral Occipital Gyrus*	1	eICV	**0.13**	**–**	**0.05**
		2	EM Construct	0.18	0.05	0.22
	EM → Left Caudal Middle Frontal Gyrus	1	eICV	0.03	–	0.39
		2	EM Construct	0.14	0.11	0.06
	Rs → Right Caudal Middle Frontal Gyrus	1	eICV	**0.19**	**–**	**0.01**
		2	RAPM	**0.21**	0.02	0.451
	Rs → Left Pars Orbitalis	1	eICV	0.11	–	0.069
		2	RAPM	0.11	0<.01	0.783
	Rs → Right Middle Temporal Lobe	1	eICV	0.29	–	0.002
		2	RAPM	**0.5**	**0.21**	**0.003**

Note. Section A reports stepwise regressions testing the indirect cognition → GM relationship via the discreet gray matter volumes that constitute the GM construct. Section B reports regressions testing the direction cognition → GM relationship between EM/Rs and the gray matter volumes implicated by the stepwise regression. All GM volumes were entered simultaneously in a stepwise fashion with inclusion criterion set to $p \leq 0.05$. *p-value* represents the significance of the predictor variable added in the step-wise regression model, and is related to the change in *R*-square.

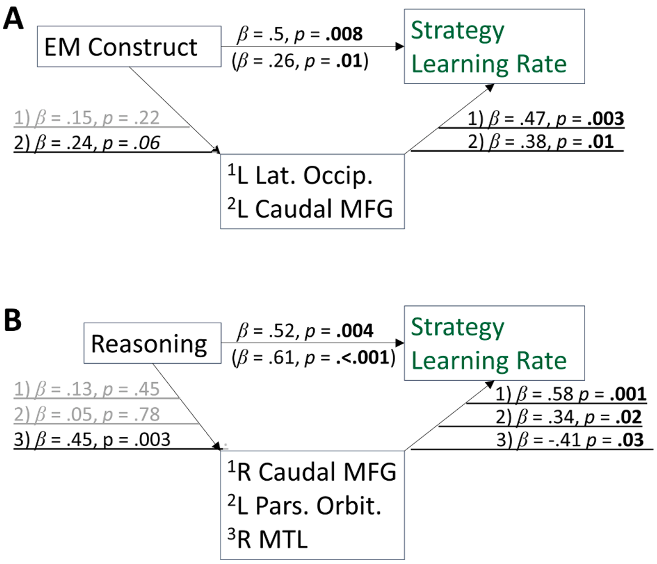


Fig. 6. Diagrams of individual gray matter volume mediation analysis of the EM → SGL and Rs → SGL relationships. Standardized Beta and significance values are given for all depicted relationships. Parenthetical values reflect the direct cognition to game learning pathway after the indirect pathway via the GM construct has been taken into account. Panel A depicts the episodic memory construct to strategy game learning relationship via individual gray matter volumes. Panel B depicts the reasoning construct to strategy game learning relationship via individual gray matter volume. "Reasoning" refers to the Ravens Progressive Matrices/RAPM task.

simpler than the representative Strategy game chosen for this study (Sushi-Go-Round) in terms of simultaneous higher-level cognitive demands, but this is true for most action games that rely less on episodic memory and working memory updating compard to strategy games. Therefore, the differential relation of Sushi-Go-Round and Tank Attack to pre-training neurocognitive measures in the present study may partially be attributed to this difference in memory-based cognitive demand between the two games. It is important to note that both games relied on quick responses, that is, processing speed.

Both the Episodic Memory and Processing Speed constructs, as well as the singular examined Reasoning measure, were found to significantly relate to learning of the Strategy game examined in this study. We hypothesized that Episodic Memory and Reasoning would relate selectively to Strategy game learning, due to the additional complexity of the Strategy game (Sushi-Go-Round), as well as the specific memory and decision making demands placed on players of Sushi-Go-Round (i.e. memorizing recipes, deciding the order in which to serve customers) compared to Tank Attack. Our results appear to validate this hypothesis. Processing speed was theorized to be a common predictor of learning on both games but this hypothesis is not supported by our results. This is further evidence that our selected action game may differ qualitatively from other studied games in the genre the learning of which was found to related to variance in processing speed. It is also worth considering that the sample examined in this study was exclusively 65 years of age or older, whereas studies that have related processing speed to performance and learning of video games have typically utilized young [4,46] or lifespan samples (i.e. [57]. Considering this, there may be a qualitative difference in the older population that reduces the influence of processing speed on action game learning.

The present study also identified a wide-ranging left-lateralized gray matter construct which was predictive of learning of the examined strategy game, visualized in Fig. 3 and reported in supplementary Table S2. This construct was found to mediate the directional, predictive relationship of both Reasoning and Episodic Memory, to Strategy game learning. While this gray matter construct did include many of the regions that we hypothesized would be related to learning of one or both of the examined games (bilateral caudal medial frontal gyrus, precentral gyrus, & supramarginal gyrus, left superior frontal gyrus), the gray matter construct as a whole is more general than our hypotheses purported. Indeed, as the construct includes the majority of the gray matter of the left cortex (as well as some equivalent volumes in the right hemisphere), this construct may better be characterized as a left-lateralized measure of total gray matter volume in the cortex. Recent work on longitudinal gray matter changes in the aging brain have suggested that a single factor of broad cortical decline is explanatory of most gray matter change that occurs later in life[24,25,67], and the gray matter construct implicated in our results may reflect how such broad changes in gray matter with age influence novel task learning.

Above-and-beyond the relationship of the broad gray matter construct to learning of the strategy game, the volume of the left caudal middle frontal gyrus was found to partially mediate the relationship between the administered Reasoning measure and learning of the strategy game. Task-positive activation in this region is known to be related to performance during both memory encoding[2] and during semantic processing[55], so it is perhaps unsurprising that it is associated with learning of the memory-intensive strategy game. However, by this conceptualization we would expect volume of the middle temporal lobe and hippocampus to more strongly mediate this relationship than caudal frontal regions. This lack of hippocampal contribution to the gray matter construct may be driven by our parcellation methodology. The version of freesurfer we utilized here (6.0) is known to have difficult in reliably parcellating deep gray matter volumes including the hippocampus[50,70]– and the noise added by this process may have prevented such regions from meaningfully capturing variance in the MFA analysis we performed. This does not however explain the lack of specific medial temporal or prefrontal influences on the EM → SGL. Recently published findingsfrom a Phase II clinical trial has found that processing-speed based cognitive training, when compared to active controls, in older adults can help with significant maintainence of caudal volume; such training-related benefots were not observed for hiipocampus [88]. Our results, along with the cited studies above, implicate that strategy video games can be considered as a tool to ameliorate age-related declines in caudate volume, which can in turn benefit memory, reasoning and processing speed.

Ancillary to the specific aims of the present study, it should be noted that, as with the earlier studies that used 5 hours or less of learning[7,57,66], the present study was able to identify factors which meaningfully differentiated individual rates of learning (one of) the examined video games with less than two hours of training on the learned task in older adults. Further, another recent publication from our group determined that differences in learning rates observed in the first five hours of practice with a novel complex game-like task was a) more sensitive to individual variance in cognitive and brain structure measure than was learning throughout the entire training period, and that b) learning rate within that first five hour period was strongly determinant of final performance on the task after 20 h of training[68]. These findings are potentially useful in designing future studies of complex task learning, as these findings suggest that learning trials of only a few hours are sufficient to meaningfully differentiate individual rates of learning. This importance of the first few hours of task learning is also evidence in the effects of cognitive training – Basak, et al [8] determined in a *meta*-analysis of cognitive training studies in healthy and MCI older adults that variance of training time above 5 h had negligible effects on training-related transfer, i.e. that only a few hours of training on a complex cognitive task was sufficient to produce transfer when the body of training literature was examined in aggregate. Collectively these results highlight the importance of early task learning in producing efficacious cognitive transfer, and demonstrate that early task learning is sensitive to a number of cognitive, structural, and lifestyle factors.

The use of off-the-shelf casual games served to benefit this study in allowing for the rapid assessment of learning in a novel, complex, and engaging task, but the use of such games also offer some limits. Firstly, compared to the specifically designed interventions such as BirdWatch Game [9] [9,68] or Space Fortress [28], commercial video games do not have integrated performance metrics suitable for precise calculation of learning rates. The creation of in-house gamified training tasks allows for accurate and scientifically relevant assessments to be embedded in the training paradigm, making capture of meaningful and interpretable learning data more likely. Second, while we endeavored to select “action” and “strategy” games which captured the essential cognitive demands of those genres, specific genre distinctions – especially as have been used in the cognitive training literature – are becoming increasingly irrelevant over time [64,91]. Future research will need to focus on specific cognitive demand profiles of training games or tasks utilized rather than relying on genre descriptions to encapsulate those cognitive demands.

CRediT authorship contribution statement

Evan T. Smith: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Kaoru Nashiro:** Supervision, Project administration, Methodology. **Margaret O’Connell:** Investigation, Formal analysis, Data curation. **Xi Chen:** Investigation, Formal analysis. **Chandramallika Basak:** Writing – review & editing, Validation, Supervision, Resources, Project administration,

Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics Statement

All procedures described in this manuscript were performed under the oversight and with the approval of the Institutional Review Board (IRB) of the University of Texas at Dallas. All participants provided informed consent prior to involvement in the study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nbas.2024.100131.

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