Original article

Effects of computer gaming on cognition, brain structure, and function: a critical reflection on existing literature

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Video gaming as a popular form of leisure activity and its effect on cognition, brain function, and structure has come into focus in the field of neuroscience. Visuospatial cognition and attention seem to benefit the most, whereas for executive functions, memory, and general cognition, the results are contradictory. The particular characteristics of video games driving these effects remain poorly understood. We critically discuss major challenges for the existing research, namely, the lack of precise definitions of video gaming, the lack of distinct choice of cognitive ability under study, and the lack of standardized study protocols. Less research exists on neural changes in addition to cognitive changes due to video gaming. Existing studies reveal evidence for the involvement of similar brain regions in functional and structural changes. There seems to be a predominance in the hippocampal, prefrontal, and parietal brain regions; however, studies differ immensely, which makes a meta-analytic interpretation vulnerable. We conclude that theoretical work is urgently needed.

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Video gaming and cognition

Video gaming, as a popular, generally cognitively demanding form of leisure activity, has received attention in recent years in search of effective, yet affordable interventions to maintain or enhance cognitive abilities in individuals in different contexts.[1-6] The increasing scientific interest in video gaming as a training instrument may be driven by an inherent playfulness of video games in contrast to classical training programs, as well as substantial effects on brain structure and function within short training periods. This is the reason for reviewing the preexisting and quite heterogeneous literature on this new interventional instrument. In this article we, first, critically discuss existing methodological challenges in the field when it comes to drawing general conclusions about video gaming and cognition. We are aiming less at summarizing existing findings on the basis of existing meta-analyses and reviews once again, but rather at addressing the complex challenges when effects of video gaming are assessed in experimental setups. To learn more about specific results in detail we would like to refer the reader to existing excellent review and meta-analytic literature.[3,5-17] In the second section we turn to the effects of video gaming on brain structure and function reported in single studies, as reviews and meta-analyses are sparse.

To start with a summary, it generally has been established that video gaming has beneficial effects on cognition, eg,

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refs 4,5,7, but see ref 18). However, the devil is in the details. Looking closer in order to make a specific statement concerning specific cognitive domains, groups of individuals, video game genres, training intensity, and transfer effects, results are mixed. This is not only true for single studies, but, in particular also for the multitude of reviews and meta-analytic studies. Depending on the studies chosen, meta-analyses report contradictory results concerning the effects of video games, eventually leaving nearly as much room for interpretation as single empirical studies despite their good quality. It seems almost impossible to outline the effect of video gaming on cognition in a simple statement without mentioning numerous limitations. The abilities with the fewest limitations to name would, most likely, be visuospatial cognition and attention.[5,7] Concerning executive functioning, memory, and general cognition, results are way more complicated and are not suited for general conclusive statements. One conclusion that can be drawn from the variety of results, however, is that theoretical work is more urgently needed than yet another empirical study, however excellently conducted it might be. Instead, stepping back and taking a look from afar in order to conceptualize research, homogenize designs, and then start all over again to evaluate whether and what effects each type of video games has on cognition should be the watchword of the day. This call is less ideologic but instead pragmatic, as without a framework from which research questions and hypotheses can be derived, the interpretation of current findings and, ultimately, the understanding of underlying mechanisms, is hampered.

Video gaming has beneficial effects on cognition, but the underlying mechanisms are not truly understood

A major critical point in evaluating possible effects of video gaming on cognition lies in the definition of "video gaming" itself. Here, studies as well as meta-analyses and reviews do not draw on a consistent definition. "Video gaming" is only useful to broadly outline the scope of a question. However, video games comprise a multitude of very different activities and content as well as (cognitive) demands. While some studies have included "type of video game" as a moderating variable into their analyses,[11] others only included studies using narrowly defined games, for example action video games or exergames.[5,7,19] Others, again, only roughly define "video game" and include a rather broad spectrum of genres.[9,10] Additionally, the release date of games is important as well. Although Wang et al[7] and Bediou et al[5] both focused on narrowly defined action video games with similar underlying definitions, Bediou et al[5] excluded studies published before the year 2000, as they argue that technical development makes games from the 1980s and 1990s rather incomparable to games from 2000 on. Studies with games from before 2000 almost certainly use substantially different games, even if they formally meet the chosen definition. Hence, even studies applying similar definitions of video gaming might differ substantially due to the timespan considered. Although overall studies report a beneficial effect of the chosen video game on cognition, the exact understanding of the underlying mechanisms remains unclear. Inferences about what within a game truly drives enhancement will remain poorly understood, because gaming mechanisms cannot be isolated and experimentally manipulated in order to test effects.

Another difficulty concerns the question of the chosen cognitive domain under study. Studies differ in the specific cognitive domain they evaluate such as processing speed, memory, global cognition, executive functioning, learning, and attentional processes, and this is even true for meta-analyses and reviews.[5,7-11] Additionally, the very same constructs are defined differently across studies. While, for example, executive functioning is considered as an entity with no effects found in the study by Wang et al,[7] in Mansor et al's[10] study it is defined and subdivided into different processes, according to Miyake et al[20] with effects on updating memory. In the study by Powers,[8] executive functions are categorized as a subdomain of information processing (for which an effect was found). In a subanalysis, executive functioning here comprises dual/multitasking, inhibition tasks, task-switching, working/short-term memory measures, intelligence tests, and executive functioning batteries resulting in negligible effects. Similar, while Sala and Gobet[18] argue that no effect can be found for general cognition, Stanmore et al[19] report a positive effect of exergames on general cognition, which is corroborated by Wang et al,[7] however, in a meta-analysis including only action video games. In yet another review, Cardoso-Leite and Bavelier[6] try to extract the effect of video gaming on attentional control as a proxy for enhancing the "ability to learn, enhance capacity for learning to learn" in children. They report effects of action video games on attentional control, but refrain from drawing general conclusions. Results cited here make it evident that, once again, generally some kind of effect on cognition is usually found, however, even on a meta-level, inferences enabling deeper understanding of underlying mechanisms are impossible. As an aside, if this is even evident on a meta-analytic level, we do not dare to discuss the tremendous heterogeneity und concomitant difficulty of operationalization issues on specific study levels (eg, cognitive domain under study, instruments chosen for assessment of domain, chosen video game to affect cognitive domain).

A third major challenge is inherent in the design of those studies and was raised by Green et al.[21] In an experimental setting, effects are evaluated in comparison with a specific control group. It is design immanent that effects are found and conditionally interpreted based on the (null)effects of the control group. However, depending on the control group chosen, a range of results are possible. There is no standardized approach which is generally applied. Reviews and meta-analyses differ in which studies they include as reference. Bediou et al[5] exclusively focused on studies that contrasted their action-game training group against an active control group, playing commercially available non-action games. Mansor et al,[10] on the other hand, explicitly excluded studies with an active gaming control group, resulting in a completely different selection of studies, yet both aiming at analyzing the effects of video gaming on cognition. In yet another meta-analysis, Wang et al,[7] only excluded studies with no control group at all. Although all meta-analyses report an overall moderate positive effect of gaming on cognition, inferences across studies contributing to understanding the underlying mechanisms of how and why effects are found are not warranted, as this would be like comparing apples and oranges. No one-fits-all solution exists for the choice of a control group; pro and con arguments can be found depending on the specific research question. However, coming full circle, with a basically mutually exclusive selection of studies, inferences must remain on a descriptive level instead of contributing to a deeper understanding of the how and why.

We consider the points discussed, that is, definition of video game, cognitive domain chosen, and control group, as crucial challenges, however, we would like to draw attention to yet another set of variables that make the interpretation of the results of existing reviews and meta-analyses difficult, as they differ between studies and their unique contribution has not yet been understood. Age, gender, and even education might influence results and, hence, render considerate sampling mandatory. Additionally, duration and frequency of training in an intervention study as well as differentiating between habitual players and novices needs careful consideration when designing and interpreting (quasi-) experimental studies.

Our points risen are neither new nor unacknowledged per se. Interestingly, existing meta-analytic literature not only contributes to the uncertainty, but also acknowledges the fact that the lack of theoretical framework and a standardized experimental protocol impedes interpretation, inferences and, in the end, accumulation of scientific knowledge (eg, ref 5). Nevertheless, up-to-date, intensified work on theoretical framework is only very slowly beginning,[22] and mainly still rather seems to generate study after study. The points risen do, also, not primarily pertain to reviews and meta-analyses, but need to be addressed at a study level. That they become visible in meta-analytic literature makes the problem only more distinct, and strongly emphasizes the call for standardized protocols as it underlines that it is not a problem of single studies but rather inherent in the system.

Video gaming and cognition at a brain structural and functional level

The reported potential improvements in cognitive domains after training with video games are accompanied and potentially caused by underlying changes in brain function and brain structure. However, at present, even less research has been conducted focusing on neural changes in addition to cognitive changes due to video game play. Only a single review on this topic has recently been published.[23] This review (in total covering n =116 articles) includes both cross-sectional designs in which habitual gamers are compared with participants who never or only seldom play video games and longitudinal intervention designs in which a randomized group is trained with a given video game and a control group is not. Moreover, it includes studies on video game-addicted populations. Here again, the challenge of the chosen control group becomes evident as effects cannot be attributed causally due to the tremendous heterogeneity of references chosen. The general conclusion might be along the lines of "video gaming has an effect on brain structure and function," although the underlying mechanisms that drive these effects might not be inferred. To start with, including studies in reviews differing in design does have its place, but needs to be supplemented by studies or reviews allowing for more causal inferences on the long run. Nevertheless, it seems that in brain regions particularly related to attention and to visual spatial skills, an improvement in terms of brain function and brain structure due to video game training can be observed.

In the present review we would like to focus on longitudinal intervention studies, as causal effects of video gaming can only be inferred from designs in which brain function or structure is compared before and after a randomly assigned training intervention. Moreover, we would like to exclude studies on problem gamers or video game addiction, since our first goal is to understand the effects of video game exposure in the healthy population and in response to a moderate dosage of game play. We also excluded studies in which the immediate effects of acute video game exposure were investigated, that is, where participants were asked to play for a time frame of minutes to hours until changes were assessed. Based on these criteria we included 22 studies[24-45] *(Table I)*. However, it should be noted that multiple studies draw on the same sample of participants (eg, refs 29, 32, 36) all resulting from one study. All (n=8)[25,26,29,31,33,41,42,44] but one study[43] on brain structural changes over time showed increases in different brain regions, with a clustering of results on growth in prefrontal and temporal brain regions (especially hippocampus). The exception is a very recent paper showing that, generally, increases in hippocampus can be observed after training with a 3D platformer game, however, with differential results being found after training with action video games, depending on the navigation strategy of the participants (with response learners showing decreases of hippocampal volume, whereas spatial learners show increases).[44] In contrast, of the 15 studies focusing on brain functional changes, 7[23,24,30,32,37,38,40] report exclusive increases in brain function, be it measured at rest or during a task-based design; the other 8[27-29,33-36,39] studies report only or also decreases in brain function. Results are inconsistent or even contradictory, however. Due to differences in study design and chosen intervention, the results cannot be interpreted

STUDY	N	AGE	SAMPLE	VIDEO GAME GENRE	COMMERCIAL/CUSTOM-MADE
Anguera et al, 2013[23]	46	67	Healthy older adults	Racing	Custom-made (goal: train multitasking)
Bailey & West, 2013[24]	31	22	Healthy adults	Action, First Person Shooter, Puzzle, Brain Training	Commercial
Colom et al, 2012[25]	20	19	Healthy young adults	Puzzle, brain training (Prof Layton)	Commercial
Diarra et al, 2019[26]	33	68	Healthy older adults	3D platform (Super Mario)	Commercial
Eggenberger et al, 2016[27]	33	75	Healthy older adults	Exergame	Commercial

Table I (continued overleaf). Selected studies (n= 22) included in the present review on effects on brain structural and functional changes. Studies are listed in alphabetical order. Upward arrows indicate increases, downward arrows indicate decreases. DTI, diffusion tensor imaging; EEG, electroencephalography; fMRI, functional MRI; fNIRS, functional near infrared spectroscopy; MRI, magnetic resonance imaging.

and integrated across studies with final conclusions drawn from them. There seems to be a strong preponderance of reported decreases of brain function in studies in which the task performed during measurement was closely related to the video game that was actually trained (n=6)[2,9,30,34,35,37,40] The direction of these results – namely decreases in brain activity due to training when the trained task is performed – are in line with previous studies on classical cognitive training in which the training tasks consist of adaptations of neuropsychological test batteries and where brain activity was measured before and after a considerable interval of training in exactly the trained task.[46-48] However, also in the later field some studies only report increases.[49] These inconsistencies could be due to the fact that the training duration and intensity differs across studies. Additionally, gains, measured by means of performance, and brain functional or structural changes are most likely not linear therefore this research field requires more studies with multiple measurement occasions so that the nonlinear trajectories of change can be observed. We have recently gathered evidence that not only may brain functional changes over the course of training show an inverted U-shape pattern,[46] but also brain structure (in this case examined during a motor training intervention),[50] showing initial increases after short-term training but decreases over longer training intervals. These first results once again strengthen the call for a theoretical framework, in which trajectories might be outlined and can then be tested in a strictly standardized research protocol.

In general, the existing studies on video game training-related brain changes that measure and report functional and structural brain data at the same time seem to reveal evidence for the involvement of similar brain regions in functional and structural changes.[29,30] However, it is difficult to conclude from the existing pool of studies whether brain changes observed across different studies occur at comparable locations in the brain. There seems to be a precedence of change observed in hippocampus, prefrontal, and parietal brain regions; however, the studies use very different genres of video games for training, which makes a meta-analytic interpretation of the brain regions that reveal changes very vulnerable. Since multiple studies use the video games Space Fortress or a 3D version of Super Mario for training, a continuous focus on these games is warranted and may then soon allow formal quantitative meta-analyses on the resulting brain changes.

TECHNIQUE	NEURAL CHANGE	TRAINING DURATION
EEG	Task-related (game play): ▲ midline frontal theta power ▲ frontal-posterior theta coherence	4 weeks
EEG	Task-related (emotional faces): ▲ P300 amplitude	2 weeks
MRI/DTI	Grey matter: ▲ PFC ▲ small temporal and parietal regions White matter: ▲ HC cingulum ▲ ILF	4 weeks
MRI	▲ frontal eye fields	6 months
fMRI/MRI	Task-related (while walking): ▼ PFC (associated with improved cognitive performance)	8 weeks

STUDY	N	AGE	SAMPLE	VIDEO GAME GENRE	COMMERCIAL/CUSTOM-MADE
Gleich et al, 2017[28]	48	24	Healthy young adults	3D platform (Super Mario)	Commercial
Haier et al, 2011[29]	26	13	Adolescents	Puzzle	Commercial
Han et al, 2011[30]	19	21	Healthy young adults	First person shooter	Commercial
Kral et al, 2018[32]	47	13	Adolescents	Empathy training	Custom-made (goal: train empathy)
Kühn et al, 2014[31]	48	24	Healthy young adults	3D platform (Super Mario)	Commercial
Kühn et al, 2017[33]	53	69	Healthy older adults	?	Custom-made (goal: train self-control)
Lee et al, 2012[34]	75	22	Healthy young adults	Action, shooter (Space Fortress)	Commercial
Lorenz et al, 2015[35]	48	24	Healthy young adults	3D platform (Super Mario)	Commercial
Maclin et al, 2011[36]	39	(19-29)	Healthy young adults	Action, shooter (Space Fortress)	Commercial

Table I (continued). Selected studies (n= 22) included in the present review on effects on brain structural and functional changes. Studies are listed in alphabetical order. Upward arrows indicate increases, downward arrows indicate decreases.
DTI, diffusion tensor imaging; EEG, electroencephalography; fMRI, functional MRI; fNIRS, functional near infrared spectroscopy; MRI, magnetic resonance imaging.

TECHNIQUE	NEURAL CHANGE	TRAINING DURATION
fMRI	Task-related (Passive win > loss game play viewing) ▼ PFC ▲ HC	8 weeks
fMRI/MRI	Grey matter ▲ PFC ▲ temporal gyrus Task-based: (during active Tetris game play) ▼ PFC ▼ parietal ▼ ACC	3 month
fMRI	Task-based (passive viewing of game scenes those who played more showed): ▲ PFC ▲ parietal	10 days
fMRI	Task-based (empathic accuracy): ▲ right temporo-parietal junction Resting state: ▲ posterior cingulate–medial PFC	2 weeks
MRI	▲ PFC ▲ HC ▲ Cerebellum	8 weeks
MRI/fMRI	Grey matter: ▲ PFC: right IFG Task-based (stop signal task): ▼ PFC: right IFG	8 weeks
fMRI	Task-based (game play): ▼ intracalcarine cortex ▼ lingual gyrus ▼ lateral occipital cortex	8 weeks
fMRI	Post vs pretest control group (reward task): ▼ ventral striatum	8 weeks
EEG	Task-based (Video game hits): ▼ P300 amplitude ▼ Delta power ▲ Alpha power (Video game enemies): ▲ P300 amplitude (Oddball tones): ▼ P300 amplitude ▲ Delta power	20 hours

STUDY	N	AGE	SAMPLE	VIDEO GAME GENRE	COMMERCIAL/CUSTOM-MADE
Martinez et al, 2013[37]	20	19	Healthy young adults	Puzzle, Brain training (Prof. Layton)	Commercial
Nikolaidis et al, 2014[38]	45	22	Healthy young adults	Action, shooter (Space Fortress)	Commercial
Prakash et al, 2012[39]	66	22	Healthy young adults	Action, shooter (Space Fortress)	Commercial
Strenziok et al, 2014[41]	42	69	Healthy older adults	Action, shooter, real time strategy, Puzzle, Brain training	Commercial
Szabo et al, 2014[42]	56	37	Healthy adults	Action, 3D platformer (Super Mario)	Commercial
Voss et al, 2011[40]	29	22	Healthy young adults	Action, shooter (Space Fortress)	Commercial
West et al, 2017[44]	21	68	Healthy older adults	Action, 3D platformer (Super Mario)	Commercial
West et al, 2018[43]	43	23	Healthy young adults	Action, 3D platformer (Super Mario) & shooter	Commercial

Table I (continued). Selected studies (n= 22) included in the present review on effects on brain structural and functional changes. Studies are listed in alphabetical order. Upward arrows indicate increases, downward arrows indicate decreases. DTI, diffusion tensor imaging; EEG, electroencephalography; fMRI, functional MRI; fNIRS, functional near infrared spectroscopy; MRI, magnetic resonance imaging.

TECHNIQUE	NEURAL CHANGE	TRAINING DURATION
fMRI	Resting state: ▲ parieto-frontal correlated activity	4 weeks (16 hours)
fMRI	Task-based (video game play) Predictors of WM performance ▲ Superior parietal lobule ▲ Post central gyrus ▲ Posterior cingulate cortex	30 hours (15 sessions)
fMRI	Task-based (video game play) Post vs pre (all groups also controls): ▼ MFG ▼ SFG ▼ vmPFC HVT vs Controls: ▼ MFG ▼ SFG	30 hours (15 sessions)
MRI (DTI)	Across all groups: ▲ lingual gyrus ▲ thalamus	6 weeks
MRI	After video game intervention ▲ hippocampus (right)	8 weeks
fMRI	Resting state: Variable priority post > pre ▲ fronto-parietal network increases in connectivity	20 hours, 2-4 weeks
MRI	▲ hippocampus (left) ▲ cerebellum	6 months
MRI	Action video game Response learners: ▼ hippocampus (right) Action video game Spatial learners: ▲ hippocampus (left) 3D platformer: Response learners: ▲ hippocampus 3D platformer: Spatial learners: ▲ entorhinal cortex Role playing video game (all) ▼ hippocampus Role playing video game Response learners: ▼ hippocampus Role playing video game spatial learners: ▼ hippocampus	90 hours

Moreover, the field desperately needs studies contrasting the behavioral and neural effects of video game training between different game genres. A first study to undertake this approach with a focus on brain structural alterations in the hippocampus compared the genres 3D platformer, action, and role play video games.[44] The authors report increases in hippocampal volume in response to 3D platformer training and decreases in response to role play game training, but most importantly they identify differential effects in particular for action video games when considering interindividual differences in navigation strategy. That is, depending on the individual's navigation strategy applied in the video game, effects are either positive or negative with respect to hippocampal volume. This study paves the way to more targeted studies on the effects of video games, focusing on the exact working mechanisms. For the purpose of recommendations to the general public on which video games may be beneficial or detrimental in terms of brain health a comparison of different video game genres may be of interest. In order to identify and understand the exact game elements that cause specific neural changes more systematic studies are required. Here it would be helpful to compare training effects of several video games from a single genre with systematic variation of its separate elements (eg, 2D vs 3D navigation, first-person vs third-person perspective, presence vs absence of reward schedules). However, for this purpose either existing commercial video games would need to be adapted, or the focus would have to be put onto custom-made video games. When looking at the studies conducted on brain structural and/or functional changes, it becomes evident that meta-analytic inferences that causally link brain structure and function to specific cognitive abilities that are all effected by specific video game training intervention is not possible according to the multitude of current studies, however well-conducted each and every one might be. Important first steps have been made in order to understand the effects of video gaming; however, future research is needed to unravel the secret of the true underlying mechanisms and relations.

Conclusions

Based on the discussion of the results and studies above, we conclude that inferences will continue to alternate between the general notion of an effect of video gaming on cognition and related brain structure and function, and the inability to make specific recommendations in the field of specific therapeutic use or detailed analyses of underlying mechanisms, structures, and processes in the brain. Although disappointing for some, for the sake of accuracy, to date there seems to be no other option than being specific. This is especially important in practical settings, in which video gaming is used therapeutically. To date, therapeutic use of video games has not been based on strong scientific evidence besides the general notion that somehow, some video games have some beneficial effects on cognition in some individuals. Also, transferring exact experimental settings with clinical samples into real patient treatment might work - however, not on the basis of truly understanding the underlying mechanisms, but rather replicating a finding on descriptive level. Put that way, the need for standardized research protocols and theoretical frameworks against which hypotheses can be tested becomes clearly evident, analogous to the idea that a statement like "diseases can be cured" as a guiding principle for specific medical treatment of a specific disease in a specific group of patients could never be sufficient. A first important step was undertaken by Green and colleagues, aimed at establishing methodological guidelines for interventions for cognitive enhancement.[21,22] However, until this aspiration is fully met, recommendations concerning specific practical use in clinical settings or general application must be waived. As a closing remark we would like to draw attention to the fact that, besides criticizing the lack of knowledge concerning the underlying mechanisms, we state that video gaming has beneficial effects on cognition that are reflected in brain structure and function. However, even this must be considered differentially[44] and with caution until underlying mechanisms are truly and causally understood. Cognition, nevertheless, is only one aspect of well-being that needs to be considered when looking at "the big picture." Possible other consequences on social, emotional, or physical well-being remain unconsidered in the present article. Nevertheless, they are important aspects to be taken into account when evaluating the overall value of video gaming.[51-54] ■

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