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Moisala, Mona

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1 **Gaming is related to enhanced working memory performance and** 2 **task-related cortical activity**

3 Moisala, M.^{a,b,c*}, Salmela, V.^{a,c}, Hietajärvi, L.^b, Carlson, S.^{d,e}, Vuontela, V.^e, Lonka, K.^{b,f},
4 Hakkarainen, K.^a, Salmela-Aro, K.^{g,h,i}, Alho, K.^{a,c}

6 ^a Institute of Behavioural Sciences, University of Helsinki, Finland

7 ^b Department of Teacher Education, University of Helsinki, Finland

8 ^c Aalto NeuroImaging, Aalto University, Finland

9 ^d Department of Neuroscience and Biomedical Engineering, Aalto University School of Science, Finland

10 ^e Neuroscience Unit, Department of Physiology, Faculty of Medicine, University of Helsinki, Finland

11 ^f Optentia Research Focus Area, North-West University, South Africa

12 ^g Cicero Learning, University of Helsinki, Finland

13 ^h Department of Psychology, University of Jyväskylä, Finland

14 ⁱ Institute of Education, University College London, United Kingdom

15 ***Correspondence:** Mona Moisala, Institute of Behavioural Sciences, University of Helsinki, P.O. Box 9

16 (Siltavuorenpenger 1 A), FI 00014 University of Helsinki, Finland.

17 mona.moisala@helsinki.fi¹

18 **Keywords:** working memory, functional MRI, gaming, adolescence, dorsolateral prefrontal cortex

19 **Abstract**

20 **Gaming experience has been suggested to lead to performance enhancements in a wide variety**
21 **of working memory tasks. Previous studies have, however, mostly focused on adult expert**
22 **gamers and have not included measurements of both behavioral performance and brain**
23 **activity. In the current study, 167 adolescents and young adults (aged 13–24 years) with**
24 **different amounts of gaming experience performed an *n*-back working memory task with**

Abbreviations: DA = digital activity; GPA = grade point average; WM = working memory; LH = left hemisphere; RH = right hemisphere; MFG = middle frontal gyrus; SPL = superior parietal lobe; Prc = precuneus; SFG = superior frontal gyrus; SMA = supplementary motor area; SDP = sociodigital participation.

25 **vowels, with the sensory modality of the vowel stream switching between audition and vision**
26 **at random intervals. We studied the relationship between self-reported daily gaming activity,**
27 **working memory (*n*-back) task performance and related brain activity measured using**
28 **functional magnetic resonance imaging (fMRI). The results revealed that the extent of daily**
29 **gaming activity was related to enhancements in both performance accuracy and speed during**
30 **the most demanding (2-back) level of the working memory task. This improved working**
31 **memory performance was accompanied by enhanced recruitment of a fronto-parietal cortical**
32 **network, especially the dorsolateral prefrontal cortex. In contrast, during the less demanding**
33 **(1-back) level of the task, gaming was associated with decreased activity in the same cortical**
34 **regions. Our results suggest that a greater degree of daily gaming experience is associated**
35 **with better working memory functioning and task difficulty-dependent modulation in fronto-**
36 **parietal brain activity already in adolescence and even when non-expert gamers are studied.**
37 **The direction of causality within this association cannot be inferred with certainty due to the**
38 **correlational nature of the current study.**

39 **1. Introduction**

40 A substantial amount of evidence has accumulated suggesting that extensive experience with
41 computer and video game playing is associated with enhancements in a wide variety of cognitive
42 domains (for reviews, see Connolly et al., 2012; Green & Bavelier, 2012; Powers et al., 2013). It has
43 been proposed that since gaming requires the player to react rapidly, monitor fast-paced concurrent
44 visual and auditory stimuli and switch flexibly between subtasks while holding information in
45 memory, this might lead to improved attentional and working memory abilities in gamers. Games
46 may, in other words, act as a cognitive enhancement tool, even though that is not their primary
47 purpose (Anguera & Gazzaley, 2015). Experimental studies focusing on attentional abilities have
48 indeed shown that gamers outperform non-gamers in tasks measuring, for example, visual selective
49 attention and the spatial distribution of visuospatial attention (Green & Bavelier, 2003), as well as

50 multiple object tracking (Trick et al., 2005; Green & Bavelier, 2006). The ability to switch flexibly
51 between tasks (Colzato et al., 2010; Karle et al., 2010; Cain et al., 2012; Green et al., 2012) and
52 perform multiple simultaneous tasks (Strobach et al., 2012) has also been shown to be superior in
53 video game players, suggesting that experience with gaming can generalize to improvements in
54 cognitive control. However, some studies have shown that gaming can have negative effects on
55 executive functions (Bailey et al., 2010). Moreover, a recent meta-analysis found negligible
56 associations between gaming experience and executive functions when only experimental studies
57 with a video-game training paradigm were taken into consideration (Powers et al., 2013).

58 In the domain of working memory, gaming has been linked to improved performance in standard
59 visual *n*-back tasks both in terms of reaction times (McDermott et al., 2014) and performance
60 accuracy (Colzato et al., 2013). Similar results have been obtained using other working memory
61 paradigms (Boot et al., 2008), and with both stationary and dynamic stimuli (Sungur & Boduroglu,
62 2012). In addition, the advantage of gaming on working memory performance seems to hold
63 irrespective of the complexity of the used stimuli or the time allotted to memory encoding (Blacker
64 & Curby, 2013). Taken together, these results suggest that gaming is linked to an improved ability
65 to maintain and flexibly update information in working memory.

66 Whether the evidence outlined above allows for any causal inferences to be made about the
67 relationship between gaming and cognition is still under debate. Some evidence exists for the notion
68 that cognitive benefits can be obtained by training non-gamers on action video games (Green &
69 Bavelier, 2003) even when the participants are older adults (Anguera et al., 2013; Belchior et al.,
70 2013). Yet, such training studies have also produced null findings (Boot et al., 2008). Further, it
71 remains unclear whether different types of games produce similar effects on cognition, as most
72 studies to date have been conducted on action video game players. The specific effects of different
73 game genres (such as strategic or roleplaying games) remains understudied, but some evidence
74 suggests that the unique aspect of each game genre may enhance different aspect of cognition (Oei

75 & Patterson, 2013). For example, it has been shown that training on spatially-orientated games
76 enhances visual cognition, while non-spatially orientated games have no such effect
77 (Subrahmanyam & Greenfield, 1994; DeLisi & Wolford, 2002).

78 The aim of the current study was to examine whether the amount of daily gaming activity affects
79 adolescents' and young adults' (aged 13-24) performance and brain activity during an *n*-back task.
80 We devised an *n*-back task which required the participants to report whether a presented vowel
81 matched a stimulus presented *n* trials previously, with the modality of the vowel switching between
82 the auditory and visual modalities at unpredictable intervals. With this task we were able to measure
83 not only working memory capacity within one sensory modality, but also the ability to switch
84 attention between sensory modalities while maintaining vowel representations in working memory.
85 We reasoned that in addition to working memory performance such cognitive flexibility might be
86 entrained by computer gaming. Our bimodal task also allowed us to determine whether gaming
87 activity affects both visual and auditory working memory. The specific effects of different game
88 types on working memory performance were also examined. Brain activity during task performance
89 was recorded using event-related functional magnetic resonance imaging (fMRI) in order to
90 determine the effects of gaming on brain activity associated with working memory or modality
91 switching.

92 Although the cognitive effects of gaming have been studied extensively, the current study provides
93 a valuable addition to this line of research for several reasons. Firstly, the participants in our study
94 were sampled from a wide age range of adolescents and young adults, whereas previous studies
95 have mostly been conducted on adults. This allowed us to examine possible age-related effects
96 contributing to the association between cognitive changes and gaming. Furthermore, our study did
97 not recruit avid or expert gamers and compare them to non-gamers, as most previous studies have
98 done. The amount of daily gaming of our participants varied from little gaming to moderate
99 amounts of gaming, meaning that our results are more generalizable to adolescents and young

100 adults in general instead of only to individuals at the extreme ends of the gaming spectrum. Finally,
101 our study incorporated not only behavioral measures but also the measurement of task-related brain
102 activity which allowed us to determine the neural underpinnings of the possible cognitive benefits
103 related to gaming. Although gamers have previously been shown to perform better at working
104 memory tasks, the cortical underpinnings of this behavioral advantage have not been studied before.
105 In fact, to our knowledge our study is the first ever to combine behavioral measures and fMRI when
106 studying the link between gaming activity and working memory performance in healthy
107 participants.

108 **2. Results**

109 ***2.1. Gaming Score and Digital Activity Score***

110 The ages and grade point averages (GPA) per age cohort and gender are displayed in **Table 1**.
111 Boxplots of the Gaming Scores for females and males in each of the three age cohorts can be seen
112 in **Figure 2A**. The Gaming Score did not differ significantly between age cohorts ($p=0.09$) but it
113 was significantly higher for males than females ($F(1,161)=6.74$, $p<0.05$, $\eta^2=0.04$). Gaming Score
114 and Digital Activity (DA) Score (i.e., the self-reported amount of daily technologically mediated
115 activity) showed a strong and significant correlation ($r=0.36$, $p<0.001$) when Age Cohort and
116 Gender were controlled for.

117

Table 1. Participant characteristics.			
Age Cohort	Gender	Age (±SD)	GPA (±SD)
13-14 yrs (n=57)	F (n=25)	13.1 (±0.4)	8.6 (±0.5)
	M (n=32)	13.3 (±0.5)	8.4 (±0.7)
16-17 yrs (n=57)	F (n=31)	16.6 (±0.5)	9.1 (±0.5)
	M (n=26)	16.6 (±0.5)	8.8 (±0.7)
20-24 yrs (n=53)	F (n=24)	20.6 (±1.3)	8.9 (±0.7)
	M (n=29)	21.9 (±0.9)	8.3 (±0.9)

118 The latent variable structure of the Gaming Scale was explored using a multidimensional item
119 response theory (MIRT) model, which produced three latent variables explaining a total of 58% of
120 the variance. Variable 1 (explaining 25% of the variance) was labeled Serious Games due to the
121 high loadings of the following game genres: role playing games, adventure games, strategic games,
122 and shooter games. Variable 2 (explaining 20% of the variance) was labeled Fun Games, as the
123 items loading most strongly onto this latent variable were: music games, exercise games, party
124 games and puzzle games. The final variable (explaining 13% of the variance) was labeled Sports
125 games, due to the high loadings of sports games and racing games onto this latent variable. The
126 loadings and communalities for the items of the Gaming scale are listed in **Table 2**. Internal
127 consistency for each of the scales was examined using Cronbach's alpha. The alphas were
128 moderate: 0.79 for Serious Games (4 items), 0.70 for Fun Games (4 items), and 0.63 for Sports
129 Games (2 items). The resulting three latent variables were used in subsequent statistical analyses as
130 a between-subjects variable in order to further examine significant effects related to Gaming Score.
131 Boxplots depicting the distribution of scores for the three latent gaming variables are presented in
132 **Figure 2B**.

Table 2. The communalities and loadings onto the three latent gaming variables for the 10 items of the Gaming scale

	Loadings			Com muna lity
	Variable 1: Serious Games	Variable 2: Fun Games	Variable 3: Sports Games	
Role playing games (e.g., World of Warcraft, Mass Effect, The Elder Scrolls, Fallout)	0.87			0.73
Adventure games (e.g., Legend of Zelda, Minecraft, Tomb Raider, Uncharted)	0.76			0.64
Strategic games (e.g., Starcraft, Civilization, Age of Empires, Total War, The Sims)	0.73			0.58
Shooter games (e.g., Grand Theft Auto, Call of Duty, Battlefield, Far Cry)	0.59			0.50
Music/dance games (e.g., Just Dance, Singstar, Rock Band)		0.79		0.62
Exercise games (e.g., Wii, MS Kinetic, Wii Sports, Your Shape)		0.68		0.51
Party games (e.g., Mario Party, Start the party)		0.58		0.43
Puzzle games (e.g., Angry Birds, Bejeweld, Tetris, Most Pogo, Puzzle Quest)		0.52		0.36
Sports games (e.g., NHL, FIFA, Tiger Woods, Madden, Football Manager)			0.94	0.87
Racing games (e.g., Gran Turismo, Mario Kart, GRID, Need for Speed)			0.45	0.52

Note. Loadings <0.4 are suppressed.

133 2.2. Behavioral results

134 The overall mean percentage of correct responses (\pm standard error of the mean, SEM) was 92.0% \pm
135 0.4%. In 3% (32/1020) of the blocks the percentage of correct responses were three standard
136 deviations lower than the mean (below 57.2%), and these blocks were excluded from further
137 analyses. General performance effects related to increasing task difficulty and modality switching
138 were studied by conducting a repeated-measures ANOVA with Memory Load (0-back, 1-back and
139 2-back) and Modality Switch (switch and no switch) as the within-subjects variables. A main effect
140 of Memory Load on performance accuracy was observed ($F(2,332)=126.06$, $p<0.001$, $\eta^2=0.34$,
141 $\epsilon=0.75$). Performance accuracy decreased with increasing Memory Load, and it was $97.4 \pm 0.3\%$ for

142 0-back, $94.7 \pm 0.4\%$ for 1-back and $86.2 \pm 0.8\%$ for 2-back ($p < 0.001$ for all pairwise comparisons).
143 Modality Switch also had a main effect on performance ($F(1,166)=6.54$, $p < 0.05$, $\eta^2=0.003$).
144 Performance accuracy was slightly lower after a modality switch ($92.3 \pm 0.4\%$) than if no switch
145 had occurred ($93.2 \pm 0.3\%$). There was also an interaction between Memory Load and Modality
146 Switch ($F(2,332)= 4.16$, $p < 0.05$, $\eta^2=0.003$, $\epsilon=0.88$), because Modality Switch had a main effect on
147 0-back ($F(1,166)=9.33$, $p < 0.005$, $\eta^2=0.05$) and 1-back ($F(1,166)=13.63$, $p < 0.001$, $\eta^2=0.07$), but not
148 the 2-back ($F(1,166)=0.31$, $p=0.58$) task.

149 When response times were studied, a main effect of Memory Load was observed ($F(2,332)=346.24$,
150 $p < 0.001$, $\eta^2=0.59$, $\epsilon=0.84$). Response times increased with increasing Memory Load, so that they
151 were 0.75 ± 0.01 s for 0-back, 0.95 ± 0.01 s for 1-back and 1.10 ± 0.02 s for 2-back ($p < 0.001$ for all
152 pairwise comparisons). Modality Switch also had a main effect on performance ($F(1,166)=87.78$,
153 $p < 0.001$, $\eta^2=0.02$), so that response times were slightly longer after a modality switch (0.95 ± 0.01 s)
154 than if no switch had occurred (0.90 ± 0.01 s). There was also an interaction between Memory Load
155 and Modality Switch ($F(2,332)= 5.96$, $p < 0.005$, $\eta^2=0.002$, $\epsilon=0.96$), but subsequent ANOVAs
156 revealed that Modality Switch had a main effect on 0-back ($F(1,166)=21.11$, $p < 0.001$, $\eta^2=0.11$), 1-
157 back ($F(1,166)=47.28$, $p < 0.001$, $\eta^2=0.22$), and 2-back ($F(1,166)=40.46$, $p < 0.001$, $\eta^2=0.20$) tasks.

158 Next, the effects of the between-subjects variables on both the percentage of correct responses and
159 response times were examined by conducting a repeated measures ANOVA with Memory Load (1-
160 back, 0-back and 2-back) as the within-subject variable. In this ANOVA, as well as in all
161 subsequent ANOVAs, Age Cohort and Gender were included as between-subjects factors, and
162 Gaming Score, DA Score and GPA as covariates. When performance accuracy was examined, no
163 significant main effect of Gaming Score ($F(1,157)=0.51$, $p=0.47$) or interaction with Memory Load
164 ($F(2,314)=2.10$, $p=0.14$, $\epsilon=0.70$) was observed. Partial correlations were also calculated in order to
165 produce correlation coefficients between Gaming Score and task performance. All reported partial
166 correlations are controlled for Age Cohort, Gender, DA Score and GPA. Partial correlations

167 suggested that there was no association between performance and Gaming Score during the 0-back
168 ($r=0.06$, $p=0.44$) or 1-back ($r=-0.07$, $p=0.40$) conditions. There was, however, a non-significant
169 trend for Gaming Score to be associated with better performance during the 2-back condition
170 ($r=0.15$, $p=0.06$). In order to study whether the trend for gaming to be associated with better
171 performance specifically during the 2-back task might be explained by increased attention and
172 vigilance during this task type, the amount of misses as well as the effects of run number during 1-
173 and 2-back tasks were studied by conducting a repeated-measures ANOVA with Run number and
174 Memory Load (1-back and 2-back) as the within-subject variables. The results showed no
175 significant interaction between Run number, Task type (1- and 2-back) and Gaming Score for either
176 the percentage of correct trials ($F(1,157)=0.68$, $p=0.41$) or misses ($F(1,157)=0.76$, $p=0.39$), nor was
177 the interaction between Task type (1- and 2-back) and Gaming Score significant for the amount of
178 miss trials ($F(1,157)=0.96$, $p=0.33$). When an ANOVA with Memory Load (1-back, 0-back and 2-
179 back) as the within-subject variable was carried out for response times, an significant interaction
180 between Gaming Score and Memory Load ($F(2,314)=3.68$, $p<0.05$, $\eta^2=0.02$, $\epsilon=0.85$) was revealed.
181 Partial correlations confirmed this interaction to be due to the fact that Gaming Score was
182 associated with shorter response times only during 2-back ($r=-0.23$, $p<0.005$), but not during 0-back
183 ($r=-0.11$, $p=0.16$) or 1-back ($r=-0.10$, $p=0.20$). When the analysis was repeated so that the three
184 latent gaming variables were used as between-subjects variables instead of Gaming Score, no
185 interactions between Memory Load and any of the latent variables were observed.

186 Next, difference measures between the n-back levels were examined. When a repeated measures
187 ANOVA for the percentage of correct responses was conducted with Memory Load (1-back vs. 0-
188 back, 2-back vs. 0-back and 2-back vs. 1-back) as the within-subject variable, a significant
189 interaction between Gaming Score and Memory Load was observed ($F(2,314)=3.77$, $p<0.05$,
190 $\eta^2=0.02$, $\epsilon=0.62$): As seen in **Figure 3A**, partial correlation calculations revealed that Gaming Score
191 was positively associated with the change in the percentage of correct responses from 1-back to 2-

192 back ($r=0.17$, $p<0.05$), but not with the change in the percentage of correct responses from 0-back
193 to 1-back ($r=-0.11$, $p=0.17$) or from 2-back to 0-back ($r=0.12$, $p=0.14$). In other words, as the
194 difficulty of the n -back task increased from 1-back to 2-back, Gaming Score was associated with
195 smaller decrements on performance accuracy. An identical ANOVA to the previous one, but with
196 mean response times as the dependent variable, did not show a significant interaction between
197 Gaming Score and Memory Load ($F(2,314)=0.97$, $p=0.33$). However, partial correlations revealed
198 that, as seen in **Figure 3B**, the association between Gaming Score and the change in response times
199 from 1-back to 2-back was significantly negative ($r=-0.17$, $p<0.05$; the higher the Gaming Score
200 was, the smaller the 2-back minus 1-back difference was), but not between Gaming Score and the
201 change in response times from 0-back to 1-back ($r=-0.03$, $p=0.73$) or from 2-back to 0-back ($r=0.12$,
202 $p=0.14$). When analyses of difference measures on performance accuracy and response times were
203 repeated using the latent gaming variables instead of Gaming Score, no significant interactions were
204 observed between Memory Load and any of the three latent variables.

205 The relationship between Gaming Score and the difference measures between n -back levels were
206 further studied by specifically examining trials directly following a modality switch (i.e., switch
207 trials). When switch trials were analyzed with Memory Load (1-back vs. 0-back, 2-back vs. 0-back
208 and 2-back vs. 1-back) as the within-subjects variable in the ANOVA, Gaming Score did not
209 demonstrate a significant main effect ($F(1,157)=0.18$, $p=0.68$) or interactions with any of the other
210 variables for the percentage of correct responses, but analysis of response times revealed an
211 interaction between Gaming Score and Memory Load ($F(2,314)=3.75$, $p<0.05$, $\eta^2=0.02$, $\epsilon=0.74$).

212 Partial correlations showed that on trials following a modality switch, Gaming Score was negatively
213 associated with the change in response times from 1-back to 2-back ($r=-0.23$, $p<0.005$; **Figure 3C**)
214 as well as from 2-back to 0-back ($r=-0.16$, $p<0.05$) but not with the change in response times from
215 0-back to 1-back ($r=0.03$, $p=0.75$). Again, when the three latent gaming variables were studied, no
216 effects on response times for the difference measures including only switch trials were observed.

217 An identical ANOVA as the previous one was conducted for trials that had not been preceded by a
218 modality switch (i.e., non-switch trials), which revealed a significant interaction between Gaming
219 Score and Memory Load ($F(2,314)=4.44$, $p<0.05$, $\eta^2=0.03$, $\epsilon=0.60$): Gaming Score was positively
220 associated with the change in the percentage of correct responses from 1-back to 2-back ($r=0.18$,
221 $p<0.05$), but not with the change from 0-back to 1-back ($r=-0.13$, $p=0.10$) or 2-back to 0-back
222 ($r=0.12$, $p=0.12$). No such interaction was found when the analysis was repeated for the three latent
223 gaming variables. Analysis of response times for non-switch trials revealed no significant main
224 effect of Gaming score ($F(1,157)=1.36$, $p=0.25$) or interactions of Gaming Score with any of the
225 other variables.

226 The modality of the working memory task did not affect the relationship between Gaming score and
227 task performance when comparing the *n*-back levels, as revealed by an ANOVA with Modality
228 (visual and auditory) and Memory Load (1-back vs. 0-back, 2-back vs. 0-back and 2-back vs. 1-
229 back) as the within-subject variables. That is, no significant interactions were observed between
230 Modality, Memory Load and Gaming score on the percentage of correct responses ($F(2,314)=0.18$,
231 $p=0.73$, $\epsilon=0.64$) or response times ($F(2,314)=0.36$, $p=0.60$, $\epsilon=0.65$). The DA score demonstrated no
232 significant effects on any of the indices of behavioral performance.

233 Age cohort was included in all ANOVAs as a between-subjects factor, so that interactions between
234 gaming and age could further be examined. However, there was no significant interaction between
235 Gaming Score and Age Cohort on performance accuracy ($F(2,157)=1.02$, $p=0.36$) or response times
236 ($F(2,157)=0.53$, $p=0.59$) when absolute values were examined, or on performance accuracy
237 ($F(2,157)=0.26$, $p=0.77$) or response times ($F(2,157)=0.27$, $p=0.76$) when relative values were
238 examined. Further, no such effects on performance accuracy or speed were observed when only
239 switch or non-switch trials were examined, or when the modality of the presented letter was
240 considered.

241 **2.3. fMRI results**

242 Cortical regions showing greater activation during 1- and 2-back than during 0-back task are
 243 depicted in **Figure 4A**. Ten Working Memory regions-of-interest (WM ROIs) were subsequently
 244 drawn to cover the regions showing maximal activity (threshold $t=5.26$, cluster size > 100 , voxel-
 245 level Familywise error corrected $p < 0.05$): left and right middle frontal gyrus (MFG; BA9), left and
 246 right superior frontal gyrus (SFG; BA6), left and right superior parietal lobe (SPL; BA7), left and
 247 right medial supplementary motor area (SMA; BA6) and left and right precuneus (Prc; BA7) ROIs.
 248 Coordinates of peak signal changes for each of the ten WM ROIs are presented in **Table 3**.

Table 3. Peak coordinates for the ten Working Memory regions-of-interest (WM ROIs).

Coordinates of peak signal changes refer to the MNI coordinate system. (MFG = middle frontal gyrus, SPL = superior parietal lobe, Prc = precuneus, SFG = superior frontal gyrus, SMA = supplementary motor area, prefix r = right hemisphere, prefix l = left hemisphere)

ROI label name	x	y	z
lMFG	-42	22	30
lSPL	-40	-44	50
lPrc	-4	-64	52
lSFG	-26	8	52
lSMA	-6	18	46
rMFG	44	30	30
rSPL	34	-42	42
rPrc	8	-64	54
rSFG	28	2	52
rSMA	6	18	48

249 Subsequent analyses were performed for all voxels within the WM ROIs.

250 The effects of Gaming Score and the other between-subjects variables on cortical recruitment
 251 within the WM ROIs were then examined. The three latent gaming variables were not included in
 252 the ROI analyses because they had no significant effects on any of the key performance measures,
 253 and the aim of the current study was specifically to examine how cognitive benefits related to
 254 gaming are reflected in cortical activity. Standardized beta values for Gaming Score produced by

255 the GLM for activity in each of the WM ROIs (while controlling for Age Cohort, Gender, DA
256 Score and GPA) are depicted in **Figure 4B**. When task-related activity modulations in the WM
257 ROIs across all trials were examined, a three-way interaction between ROI, Memory Load (1-back
258 vs. 0-back, 2-back vs. 0-back and 2-back vs. 1-back) and Gaming Score was observed
259 ($F(18,2826)=2.82$, $p<0.01$, $\eta^2=0.004$, $\epsilon=0.41$). When an ANOVA was conducted for each WM ROI
260 separately, an interaction between Gaming Score and Memory Load (1-back vs. 0-back, 2-back vs.
261 0-back and 2-back vs. 1-back) was observed specifically in the left MFG ($F(2,314)=5.75$, $p<0.01$,
262 $\eta^2=0.03$) and right MFG ($F(2,314)=5.28$, $p<0.05$, $\eta^2=0.03$) ROIs. Gaming Score was negatively
263 associated with the 1-back vs. 0-back activity differences in both the left and right MFG ($b=-0.07$,
264 $t(157)=2.44$, $p<0.05$ and $b=-0.08$, $t(157)=2.31$, $p<0.05$, respectively). Conversely, Gaming Score
265 was positively associated with the 2-back vs. 1-back activity difference in the same ROIs ($b=0.09$,
266 $t(157)=2.81$, $p<0.01$ and $b=0.10$, $t(157)=2.70$, $p<0.01$, respectively). For the subtraction between 2-
267 and 0-back, no effect of Gaming score was observed for either the left or right MFG ($b=0.03$,
268 $t(157)=0.63$, $p=0.68$ and $b=0.01$, $t(157)=0.29$, $p=0.77$, respectively). In other words, the higher the
269 Gaming Score of a participant, the smaller the change in MFG activity from 0-back to 1-back, but
270 the greater the change in MFG activity from 1-back to 2-back. There was a significant correlation
271 between activity and task performance during 2-back task in the left and right MFG ($r=0.18$, $p<0.05$
272 and $r=0.25$, $p<0.005$, respectively) as well as the left and right SPL ($r=0.16$, $p<0.05$ and $r=0.26$,
273 $p<0.005$, respectively), when controlling for Age Cohort, Gender, DA Score and GPA. Mediation
274 analysis was therefore conducted for the left and right MFG ROIs, since they showed an association
275 between both Gaming Score and activity, as well as performance accuracy and activity. The
276 mediation analysis revealed that for the left MFG, the model with both Gaming Score and
277 performance accuracy predicting activity in the ROI during 2-back was not significant
278 ($F(5,161)=1.30$, $p=0.27$) and there was no indirect effect of Gaming Score on ROI activity mediated
279 by performance accuracy as demonstrated by the Sobel test ($Z=0.80$, $p=0.43$). For the right MFG,

280 the model with both Gaming Score and performance accuracy predicting activity in the ROI during
281 2-back was significant ($F(5,161)=2.31, p<0.05, R^2=0.07$) so that Gaming Score remained a
282 significant predictor in this model ($\beta=0.04, t(161)=2.10, p<0.05$) and no indirect effect of Gaming
283 Score on ROI activity was observed ($Z=1.29, p=0.19$).

284 When only switch trials were included in the analyses, a three-way interaction between ROI,
285 Memory Load and Gaming Score was observed ($F(18,2826)=2.28, p<0.05, \eta^2=0.003, \epsilon=0.45$).
286 ANOVAs conducted separately for each WM ROI showed an interaction between Gaming Score
287 and Memory Load (1-back vs. 0-back, 2-back vs. 0-back and 2-back vs. 1-back) specifically in the
288 left MFG ($F(2,314)=3.96, p<0.05, \eta^2=0.02, \epsilon=0.84$) and right MFG ($F(2,314)=3.60, p<0.05,$
289 $\eta^2=0.02, \epsilon=0.88$) ROIs. A similar result was obtained when only non-switch trials were taken into
290 consideration: a three-way interaction between ROI, Memory Load and Gaming Score was again
291 observed ($F(18,2826)=2.21, p<0.05, \eta^2=0.003, \epsilon=0.40$), and ANOVAs conducted for each WM ROI
292 separately showed an interaction between Gaming Score and Memory Load specifically in the left
293 MFG ($F(2,314)=4.56, p<0.05, \eta^2=0.03, \epsilon=0.73$) and right MFG ($F(2,314)=4.83, p<0.05, \eta^2=0.03,$
294 $\epsilon=0.70$) ROIs.

295 The modality of the working memory task did not affect the relationship between Gaming Score
296 and activity in the WM ROIs, as no significant interactions were observed between Modality,
297 Memory Load (1-back vs. 0-back, 2-back vs. 0-back and 2-back vs. 1-back) and Gaming Score
298 ($F(2,314)=0.85, p=0.39, \epsilon=0.65$), or Modality, Memory Load, Gaming Score and ROI
299 ($F(18,2826)=0.50, p=0.84, \epsilon=0.39$). Also, Gaming Score did not demonstrate a significant effect on
300 the gray matter volume in the WM ROIs ($F(10,148)=0.96, p=0.48$).

301 **3. Discussion**

302 In the current study, gaming experience was observed to be related to enhancements in working
303 memory functioning. More specifically, a positive association was found between gaming and

304 performance accuracy, so that the higher the Gaming Score, the less performance was affected by
305 an increase in working memory load from 1-back to 2-back. Gaming was found to be associated
306 with faster response times during the 2-back task along with a nonsignificant trend for better
307 performance, but the majority of significant behavioral findings relate specifically to the difference
308 in performance as working memory load was increased from 1- to 2-back. This suggests that in the
309 current study, gaming was a significant factor in determining how performance changes as the
310 burden on working memory functioning increases. Improved performance accuracy related to
311 gaming was observed both for trials which had been preceded by a modality switch and for trials
312 without a preceding modality switch. In addition, gaming was associated with smaller increases in
313 response times when working memory load was increased from 1-back to 2-back. Closer inspection
314 revealed that these faster response times were specific to trials immediately following a modality
315 switch. The modality in which the working memory task was performed did not affect the
316 relationship between gaming and task performance. Overall, these behavioral findings suggest that
317 gaming is related to improvements in both response speed and the ability to monitor and update
318 information in working memory irrespective of the presentation modality of the task, as well as to
319 the ability to switch between the auditory and visual modalities in response to an unexpected cue
320 while performing a working memory task. This lends support to the notion that gaming affects more
321 general aspects of working memory such as the ability to effectively remove irrelevant items from
322 working memory and update its' content effectively (Colzato et al., 2013), as well as the ability to
323 recover from attention shifts (Colzato et al., 2010; Karle et al., 2010; Cain et al., 2010; Green et al.,
324 2012) while performing a working memory task. The behavioral benefits noted in the current study
325 were not specific to any certain type of game, but to the extent of gaming activity in general. This
326 suggests that although unique aspects of different types of games may train at least partially distinct
327 facets of cognition (Oei & Patterson, 2013), common features of the gaming experience are most
328 relevant to the more general aspects of working memory functioning observed here.

329 On a more general level, the behavioral findings of our study can tentatively be seen to endorse the
330 notion that games can exercise cognitive faculties (Anguera & Gazzaley, 2015), although a direct
331 causal relationship cannot be inferred solely based on our results. It is important to note that due to
332 the cross-sectional nature of the current study, the observed association between working memory
333 functioning and gaming could be explained by pre-existing differences between participants, and
334 not by training effects induced by gaming per se. There is evidence, however, that working memory
335 capacity can be trained with computerized regimes (Harrison et al., 2013; Toril et al., 2016; von
336 Bastian & Oberauer, 2013), suggesting that a direct causal relationship between gaming and
337 working memory enhancements could exist. Another pitfall of cross-sectional studies on gaming is
338 related to subject recruitment: gamers might perform better simply because they are expected to
339 (Boot et al., 2011). This confounding factor can be ruled out in the current study, however, because
340 our participants were not grouped into expert gamers and novices and they were not aware of the
341 precise purpose of the study, and they could therefore not be influenced by knowing their group
342 membership. A significant finding in the present study was also the lack of age-related influence on
343 the relationship between gaming and improved working memory. Age was not a significant
344 interacting factor with gaming experience for any of the performance indices, suggesting that the
345 coupling between gaming and cognition is detectable already in adolescence. This presents a
346 valuable extension to previous gaming studies, which have almost exclusively recruited adult
347 participants. Future research would likely benefit from recruiting even younger participants in order
348 to determine at what age the benefits of gaming become detectable. If no pattern of linear increase
349 in the correlation between gaming and performance is observed with age even when recruiting
350 younger participants, this would suggest that inborn differences in cognitive capacity may underlie
351 the performance benefits of gamers.

352 Our study is the first of its kind to examine not only the behavioral benefits related to gaming, but
353 also the cortical underpinnings of these benefits. When brain activity was examined, a fronto-

354 parietal network was consistently activated across participants when the task conditions taxing
355 working memory (1- and 2-back) were compared with the control condition (0-back). This network
356 has repeatedly been shown to be involved in a wide variety of versions of the *n*-back working
357 memory paradigm (for a meta-analyses, see Owen et al., 2005; Rottschy et al., 2012). When the
358 relationship between gaming and activity within the fronto-parietal network was studied, the results
359 revealed that this relationship differed according to task difficulty. During the less demanding *n*-
360 back task level (1-back), gaming was associated with a smaller increase in activity especially in
361 dorsolateral prefrontal regions when compared to the control condition. In contrast, as the difficulty
362 of the task was increased from 1-back to 2-back, gaming was associated with a significantly greater
363 increase in activity in the same cortical regions, coupled with enhanced behavioral performance.
364 This effect did not depend on whether a modality switch had or had not occurred prior to the trial,
365 or on the modality of the working memory task. Our study is therefore the first to demonstrate that
366 gamers might show improved working memory performance due to a “boost” specifically in
367 prefrontal recruitment when task conditions become adequately challenging.

368 The relationship between the extent of neural recruitment and cognitive performance is still unclear,
369 and therefore the effects of gaming experience on fronto-parietal recruitment during the working
370 memory task observed in the current study cannot be interpreted in a straightforward manner.
371 According to the neural efficiency hypothesis, greater individual cognitive capacity as well as
372 repeated training is coupled with lesser cortical activity during problem solving, reflecting more
373 efficient recruitment of the cortex (Haier et al., 1988). In line with this hypothesis, Bavelier et al.
374 (2012) found reduced activity in the fronto-parietal network for gamers during a visual selective
375 attention task. Likewise, Heinzl et al. (2016) observed decreased activity in right prefrontal regions
376 in older adults during an *n*-back task as a result of repeated training on the task. On the other hand,
377 training on a working memory task has been associated both with increased activity in prefrontal
378 and parietal cortices (Olesen et al., 2004), as well as with no changes in cortical activity at all

379 (Nussbaumer et al., 2015). These apparently contradictory findings as well as the results of the
380 current study may be explained by the moderating effect of task difficulty. During only moderately
381 difficult tasks, individuals with a greater cognitive capacity or better cognitive skills may need to
382 recruit less cortical resources to achieve the same behavioral performance level as other individuals.
383 In contrast, when more effort is required, these individuals recruit task-relevant brain regions to a
384 greater extent and exhibit superior performance, perhaps because a different cognitive strategy is
385 used to accomplish the task (Rypma et al., 2002). The use of an alternate strategy is supported by
386 the fact that in the current study, gaming-related differences were noted only in lateral prefrontal
387 regions. Although the fronto-parietal cortical network recruited by the working memory task in the
388 current study comprises of domain-general regions activated by a wide range of cognitively
389 demanding tasks (Duncan, 2010), specialized functions have nevertheless been assigned to
390 subregions of the frontal and parietal lobes. The specific contribution of dorsolateral prefrontal
391 regions to working memory remains a topic of debate, but it has been suggested that these regions
392 play an essential role in organizing working memory content. For example, organizing working
393 memory items into higher-level groups in order to aid memorization has been shown to produce
394 activity specifically in the lateral frontal cortex (Bor et al., 2003, 2004) and patients with lesions to
395 these same regions have exhibited inefficient use of organizational strategies during working
396 memory tasks (Owen et al., 1996). It is therefore possible that gaming experience translates into
397 better working memory performance because of the use of more efficient organization strategies,
398 seen as changes in the recruitment of frontal regions exclusively. An alternative explanation for the
399 observed results is that highly functioning individuals may become inattentive during unchallenging
400 tasks and therefore display heightened vigilance and more focused attention during more
401 demanding tasks, thus leading to the observed pattern of cortical activity in response to changes in
402 task demands. Our behavioral results do not support this explanation, however, as gaming was not
403 linked to more misses (reflecting inattentiveness) or to decrements in performance from the first

404 task block to the second (reflecting difficulties in sustaining attention on the task over longer time
405 periods) during the easier *n*-back task condition. Taken together, our results provide evidence for a
406 more complex relationship between neural recruitment and cognitive performance than outlined by
407 the neural efficiency hypothesis (Haier et al., 1988). Both the underlying cognitive capacity of the
408 individual and the level of challenge offered by the cognitive task should be considered, as it is not
409 either factor alone which affects neural recruitment, but rather their interaction and the cognitive
410 strategies used to accomplish the task.

411 In sum, the current study replicates previous findings linking gaming to improved working memory
412 functioning (e.g., Blacker & Curby, 2013; Boot et al., 2008; McDermott et al., 2014; Sungur &
413 Boduroglu, 2012), and extends these findings to apply not only to adults but also to adolescents, and
414 to participants representing a much broader spectrum of gaming experience than just expert gamers
415 and novices. Furthermore, the current study provides novel insight into the neural basis of working
416 memory enhancements in gamers by demonstrating that the pattern of prefrontal recruitment is
417 significantly altered when working memory load is increased in participants with more gaming
418 experience. Future studies would benefit greatly from utilizing similar task-related fMRI
419 measurements as in the current study, but in a pre-post game training paradigm where cortical
420 activity during a working memory task would be recorded both before and after game training. This
421 would help to determine whether gaming really causally alters how the fronto-parietal network is
422 recruited when working memory is heavily taxed, and it would further elucidate the relationship
423 between neural recruitment and cognitive performance.

424 **4. Conclusions**

425 A positive association between daily gaming activity and working memory performance of
426 adolescent and young adult participants was demonstrated in the current study. More specifically,
427 higher levels of self-reported daily gaming activity were linked to smaller performance decrements

428 when working memory load was increased, both in terms of performance accuracy and response
429 times. In addition, response times during the working memory task were less affected by a modality
430 switch the higher the gaming activity level of the participant was. When brain activity was
431 measured, gaming was associated with a smaller increase in activity especially in dorsolateral
432 prefrontal regions when working memory was only moderately taxed. As the difficulty of the
433 working memory task was increased, gaming was associated with a significantly greater increase in
434 activity in the same cortical regions, possibly reflecting an alternative cognitive strategy used to
435 perform the task. The results of the current study extend previous findings on gaming and working
436 memory enhancements to apply to adolescents and young adults with moderate levels of gaming
437 activity, and elucidate the neural underpinnings of the observed cognitive benefits linked to gaming.

438 **5. Experimental procedure**

439 **5.1. Participants**

440 The participants were selected from a sample of 2977 respondents, who had filled out a
441 questionnaire including a wide variety of questions relating to the daily use of digital technologies
442 as a part of the research project titled Mind the Gap between Digital Natives and Educational
443 Practices (2013–2016) (<http://wiredminds.fi/projects/mind-the-gap/>). The respondents belonged to
444 three different age cohorts: 13–14- and 16–17-year-old lower and upper secondary students and 20–
445 24-year-old university students (cohorts 1, 2, and 3, respectively). The questionnaire included a
446 Sociodigital Participation (SDP) inventory (Hietajärvi et al., 2015) assessing various dimensions of
447 technology-mediated practices in everyday life. The participants (each cohort separately) were first
448 grouped into profiles representing their SDP practices using a latent profile analysis (Vermunt &
449 Magidson, 2002). The identified profiles (across cohorts) were then interpreted as basic
450 participators (control; n=1925 in total, n=59 in the current study) who demonstrated the least
451 technologically-mediated activity, gaming-oriented participators (n=656 in total, n=54 in the current

452 study), who focused especially on action and social gaming as separated from recreational gaming,
453 and creative participators (n=388 in total, n=54 in the current study) characterized by intensive
454 engagement in socio-digital activities in general and creative use of knowledge and media in
455 particular. Respondents who demonstrated the highest likelihood of belonging to their respective
456 profiles were then asked to participate in the fMRI study. **Figure 1** depicts all of the questionnaire
457 respondents in a scatterplot so that the colors of the circles denote the SDP profile of each
458 respondent, and filled circles denote respondents who are included in the analyses of the current
459 study. The respondents are plotted against two discriminant functions produced by a linear
460 discriminant function analysis (conducted for the purpose of this data visualization), where SDP
461 profile was the grouping variable, and the predictor variables were a total of 27 items from the SDP
462 inventory assessing technology-mediated activities (e.g., the use of social media, playing different
463 genres of computer games, creating content to share online). Both functions produced by the
464 discriminant analysis were significant (Wilks Lambda=0.17, $\chi^2(78)=5220.42$, $p<0.001$ and Wilks
465 Lambda=0.58, $\chi^2(38)=1582.81$, $p<0.001$), which was to be expected since the majority of the
466 predictor variables were used when conducting the original SPD grouping. The first function was
467 principally explained by playing various genres of computer games, online gaming activity and
468 considering gaming as one's hobby, so this function was termed Gaming activity. The second
469 function was principally explained by sharing content such as videos, photos or status updates
470 online, so this function was termed Creative activity. The SDP profiles were only used to sample
471 participants but not in any further analyses, as all participants demonstrated some level of gaming or
472 socio-digital activity. Although the purpose of the current study was to examine gaming-related
473 effects, representative creative participators were recruited as participants due to the fact that the
474 current study is part of a larger effort to investigate a variety of technology-related activities (such
475 as media multitasking; Moisala et al., 2016). It also enabled us to recruit participants exhibiting
476 varying degrees of gaming activity instead of only including participants from the far ends of the

477 gaming spectrum, thus strengthening the generalizability of our results. Respondents ineligible for
478 an fMRI measurement and respondents with any learning difficulties or notably poor school
479 performance with a self-reported grade point average (GPA) below 7 on a 4-to-10 point scale
480 system were screened out. In total, brain activity and performance of 173 participants were
481 measured for the study. Out of the measured participants, 6 participants were discarded from further
482 analyses due to technical difficulties in data measurement or bad data quality. As a result, a total of
483 167 healthy volunteers were included in the analyses (**Table 1**), with 57 participants in cohort 1, 57
484 in cohort 2 and 53 in cohort 3. A subset (n=149) of these same participants were used in a
485 previously published study linking media multitasking activity to increased distractibility and right
486 prefrontal cortical activity (Moisala et al., 2016). All participants were native Finnish speakers with
487 normal hearing, normal or corrected-to-normal vision, and no self-reported history of psychiatric or
488 neurological illnesses. An informed written consent was obtained from each participant (and from a
489 guardian in the case of underage participants) before the experiment. The experimental protocol was
490 approved by the Ethics Committee for Gynaecology and Obstetrics, Pediatrics and Psychiatry of
491 The Hospital District of Helsinki and Uusimaa, Finland.

492 **5.2. Gaming Score**

493 A sum of scores from 10 items comprising a Gaming scale was calculated based on the SDP
494 inventory and used as the Gaming Score. The Gaming scale probed how often the participants play
495 different types of computer and video games. These 10 gaming types were: Fun (e.g., Mario Party,
496 Start the Party), Exercise (e.g., Wii Sports, MS Kinetic), Music/dance (e.g., Just Dance, Singstar),
497 Puzzle (e.g., Angry Birds, Bejeweled), Sports (e.g., NHL, FIFA), Racing (e.g., Gran Turismo,
498 Mario Kart), Role playing (e.g., World of Warcraft, Fallout), Strategic (e.g., Starcraft, Civilization),
499 Shooter (e.g., Call of Duty, Battlefield) and Adventure (e.g., Minecraft, Uncharted) games.
500 Participants were asked how much time they spend playing each game type on either a mobile
501 device, gaming console or computer, and responses were given on a 7 point Likert scale (1=never,

502 2=a few times a month, 3=monthly, 4=weekly, 5=daily, 6=multiple times a day, 7=all the time).

503 The Gaming scale is included in the supplementary material. A univariate analysis of variance

504 (ANOVA) with the between subject factors Age Cohort and Gender was conducted with Gaming

505 Score as the dependent variable. In order to examine whether any significant findings related to

506 Gaming Score were explained specifically by certain types of games instead of overall gaming

507 activity, the latent variable structure of the data was examined in order to group gaming genres. The

508 factorability of the Gaming scale items were deemed sufficient, as i) all items correlated at least 0.3

509 with at least one other item, ii) the Kaiser-Meyer-Olkin measure of sampling adequacy (0.77) was

510 above the commonly recommended value of 0.60, iii) Bartlett's test of sphericity was significant

511 ($\chi^2(45)=459.44, p<0.001$), and iv) the diagonals of the anti-image correlation matrix were all over

512 0.50. Since the Gaming scale used a Likert response scale producing mostly non-normally

513 distributed ordinal data, its latent variable structure was modeled using a multidimensional item

514 response theory (MIRT) model (the graded response model using polychoric correlations; Holgado-

515 Tello et al., 2010; Rigdon & Ferguson, 1991), which is thought of as an equivalent to nonlinear

516 factor analysis (Takane & De Leeuw, 1987). The last five response categories in the 7-point Likert

517 scale of the Gaming scale were collapsed due to small number of data points in these three

518 categories. MIRT analysis was conducted using the statistical software R (R Core Team, 2016) and

519 its Psych toolbox (Revelle, 2016).

520 **5.3. Digital Activity Score**

521 A sum of scores from 17 items probing the amount of time spent using digital technologies was

522 calculated based on the SDP inventory and used as the DA Score. Examples of these items are: "I

523 send text messages", "I talk on the phone", "I watch movies on the computer", "I send e-mails" and

524 "I play games on the computer". Participants indicated how much time they spent with each activity

525 on a 7-point scale. Partial correlations between Gaming Score and DA Score controlling for Gender

526 and Age Cohort were calculated. The DA Score was used in all ANOVAs as a covariate in order to

527 ensure that any observed effects related to gaming would not be explained by the level of overall
528 daily digitally mediated activity.

529 **5.4. Stimuli**

530 The visual stimuli used in the *n*-back task were vowels (the Finnish vowels a, e, u and y), presented
531 in the middle of a video screen. The vowels were presented in four different fonts (Arial, Castellar,
532 Comic Sans MS and Bradley Hand ITC). The font of each vowel was assigned randomly, but if the
533 vowel in the 1- or 2-back condition matched a vowel presented 1 or 2 trials back, respectively, it
534 was never written in the same font as the vowel preceding it *n* trials back so that vowels could not
535 be matched purely based on their physical properties. The size of the vowels was 1.43° horizontally
536 and vertically. The vowel was surrounded by a square (2.86° horizontally and vertically) with a
537 fixation point in the center, both of which were on the screen throughout the entire block. The
538 vowels, surrounding square and fixation point were all white, while the background was grey. The
539 video screen where the visual stimuli were displayed was projected onto a mirror mounted on the
540 head coil.

541 The auditory stimuli in the *n*-back task were spoken Finnish vowels (/a/, /e/, /u/ and /y/). The vowels
542 were spoken by four different native Finnish speakers (2 males, 2 females). The voice in which each
543 vowel was spoken was assigned randomly, but if the vowel in the 1- or 2-back condition matched a
544 spoken vowel presented 1 or 2 trials back, respectively, it was never spoken by the same person as
545 the *n*-back vowel. The spoken vowels were presented binaurally through insert earphones
546 (Sensimetrics model S14; Sensimetrics, Malden, MA, USA). All spoken vowels were high-pass
547 filtered with a cut-off at 100 Hz and low-pass filtered with a cut-off at 7000 Hz. The intensity of the
548 spoken vowels was adjusted so that their total power in RMS units, the square root of the mean of
549 the squared signal, was similar (0.1). The intensity of the spoken vowels was individually set to a
550 loud, but pleasant level, and it was ~80 dB SPL as measured from the tip of the earphones, while

551 noise from the MRI scanner (maximum ~130 dB) was attenuated by the earplugs, circumaural ear
552 protectors (Bilsom Mach 1, Bacou-Dalloz Inc., Smithfield, Rhode Island, USA), and viscoelastic
553 mattresses around the head coil. All adjustments to the auditory stimuli were made using Audacity
554 (<http://audacity.sourceforge.net>) and Matlab (Mathworks Inc., Natick, MA, USA) softwares.

555 **5.5. *fMRI/MRI data acquisition***

556 A 3 T MAGNETOM Skyra whole-body scanner (Siemens Healthcare, Erlangen, Germany) with a
557 20-channel head coil was used for functional brain imaging. The functional echo planar (EPI)
558 images were acquired using a gradient echo sequence with an imaging area consisting of 43
559 contiguous oblique axial slices (TR 2500 ms, TE 32 ms, flip angle 75°, voxel matrix 64 x 64, field
560 of view 20 cm, slice thickness 3.0 mm, in-plane resolution 3.1 mm x 3.1 mm x 3.0 mm). Image
561 acquisition was performed at a constant rate (i.e., image acquisition was not jittered), but was
562 asynchronized with stimulus onsets. Two functional runs of 155 volumes (including 4 initial
563 dummy volumes) were measured. The duration of one block was 7 minutes, so during a total of 14
564 minutes, 310 functional volumes were obtained.

565 High-resolution anatomical images (voxel matrix 256 x 256, in-plane resolution 1 mm x 1 mm x 1
566 mm) were acquired from each participant before the *n*-back task blocks began.

567 **5.6. *Procedure***

568 Participants performed three levels of the *n*-back task in separate blocks: 0-, 1- and 2-back. **Figure**
569 **5** depicts the experimental setup of the *n*-back task. In the beginning of each block, instructions for
570 the current *n*-back task level were shown for 6 s. In subsequent task blocks, 32 vowels (visual or
571 auditory) were presented, each with a duration of 500 ms. The modality of the presented vowel was
572 switched randomly on every 3rd, 4th, 5th or 7th vowel, so that participants were not able to anticipate
573 a modality switch. Seven modality switches occurred in a block. Each vowel was followed by a
574 2500-ms retention period during which the participants were instructed to respond. In the control

575 (0-back) condition, this meant responding with the appropriate button press whether the presented
576 vowel had been presented visually or auditorily using their right index or middle finger,
577 respectively. In the 1-back and 2-back conditions, this meant responding with an appropriate button
578 press on each trial whether the vowel did or did not match the vowel presented n trials back
579 (irrespective of whether the preceding vowel n trials back was a written or a spoken one) using their
580 right index or middle finger, respectively. There were 10 match trials in each block of 32 trials. The
581 guess level (i.e., if the participant responds randomly) was 50 %. In turn, by adopting a strategy of
582 consistently responding that the vowel was not a match would have led to a correct response
583 percentage of $22/32 = 68.75$ %. During the retention period or when only auditory stimuli were
584 presented, only the square surrounding the vowels and the fixation point remained on the screen. At
585 the end of each block, the participant was shown the percentage of correct responses in that block.
586 The score was shown for 3 s.

587 There were two functional runs, 3 blocks in each run, and 32 trials (i.e., vowels) in each block. Each
588 run included one block of each n -back task level presented in a random order. This resulted in a
589 total of 64 trials for each n -back task level. Before beginning the n -back task, the participants had
590 performed an unrelated attention task described in Moissala et al. (2016) and had, therefore, already
591 spent around 30 minutes in the scanner. Although all of the participants completed both the
592 attention and the working memory task, the two tasks were specifically designed to study media
593 multitasking and gaming, respectively, according to a priori hypotheses based on existing literature.
594 The aim of the attention task was to see if a relationship between media multitasking and
595 distractibility could be detected by using a more ecologically valid experimental task than the
596 standard attention tasks used previously. Associations between working memory and media
597 multitasking were not explored, as the existing literature did not provide basis to assume that such
598 associations would exist. The working memory task, in turn, was used to study cognitive
599 performance exclusively in relation to gaming. A more standard working memory task was used in

600 this case to ensure that the neural basis of performance enhancements related to gaming could be
601 explored.

602 **5.7. Analysis of behavioral data**

603 The total percentage of correct responses for each n -back task level was calculated. Blocks where
604 the percentage of correct responses was more than three standard deviations below average were
605 removed from all further analyses. General task-related effects were examined by conducting a
606 repeated-measures ANOVA with Memory Load (0-back, 1-back and 2-back) and Modality Switch
607 (switch and no switch) as the within-subjects variables. A repeated measures ANOVA was then
608 conducted for both the percentage of correct responses as well as response times with Memory
609 Load (1-back, 0-back and 2-back) as the within-subject variable, Age Cohort and Gender as
610 between-subjects factors, and Gaming Score, DA Score and GPA as covariates. Partial correlation
611 coefficients were calculated between Gaming Score and the percentage of correct responses,
612 response times and the percentage of misses (i.e., not detecting a match), while controlling for Age
613 Cohort, Gender, DA Score and GPA. The same ANOVA and partial correlation calculations were
614 also conducted for difference measures between n -back levels (i.e., by subtracting the percentage of
615 correct responses between 1- and 0-back, 2- and 0-back, and 2- and 1-back). Further, the same
616 ANOVA was conducted separately for switch trials and for non-switch trials. In addition, a
617 repeated-measures ANOVA was conducted for the percentage of correct responses and response
618 times for non-switch trials with Modality (visual and auditory) and Memory Load (1-back vs. 0-
619 back, 2-back vs. 0-back and 2-back vs. 1-back) as within-subject variables, Age Cohort and Gender
620 as between-subjects factors, and Gaming Score, DA Score and GPA as covariates. A repeated-
621 measures ANOVA was also carried out for both the percentage of correct responses as well as
622 misses with Run number and Memory Load (1-back and 2-back) as the within-subject variables,
623 Age Cohort and Gender as between-subjects factors, and Gaming Score, DA Score and GPA as
624 covariates. ANOVAs and partial correlation calculations producing significant main effects or

625 interactions relating to Gaming Score were repeated using the latent variable scores extracted from
626 the 10 items of the Gaming scale. These analyses were conducted so that the Gaming Score was
627 replaced as the between-subjects variable by the three latent gaming variable scores, so that all three
628 latent variable scores were included in the same ANOVA/partial correlation calculation.

629 Eta squared (η^2) was calculated for all conducted ANOVAs as a measure of effect size. For all
630 conducted ANOVAs the Greenhouse-Geisser p-value was used (as indicated by the correction value
631 ϵ) if the Mauchly's test of sphericity showed a significant result for a variable with more than two
632 levels. However, original degrees of freedom will be reported with the F-value even in these cases.
633 A 95% confidence interval was used in all ANOVAs. When an ANOVA yielded a significant
634 result, Bonferroni post hoc tests were conducted. IBM SPSS Statistics 21 for Windows (IBM SPSS,
635 Armonk, NY, USA) was used for statistical analyses.

636 *5.8. fMRI data analysis*

637 The preprocessing and statistical analysis of fMRI data was performed using Statistical Parametric
638 Mapping (SPM12) analysis package (Wellcome Department of Cognitive Neurology, London, UK;
639 Friston et al., 1994) as implemented in Matlab. The first four dummy volumes were excluded from
640 analysis to allow for initial stabilization of the fMRI signal. During pre-processing, the slice timing
641 was corrected, data were motion corrected, high-pass filtered (cut-off at 1/128 Hz), and spatially
642 smoothed (6 mm Gaussian kernel). The EPI images were intra-individually realigned to the middle
643 image in each time series and un-warping was performed. Then the anatomical images were
644 normalized to a canonical T1 template (MNI standard space) provided by SPM12 and the
645 transformations were then used as a template to normalize the functional volumes for each
646 participant (tri-linear interpolation, 3 mm x 3 mm x 3 mm using 16 nonlinear iterations).

647 The regressors included in the GLM for the first-level statistical analysis are listed in **Table 4**.

Table 4. List of the regressors included in the GLM for the first-level statistical analysis of fMRI data.

Task-related regressors:

- 1) 0-back trials immediately preceding a modality switch with vowel presented visually
- 2) 0-back trials immediately following a modality switch with vowel presented visually
- 3) All other 0-back trials with vowel presented visually
- 4) 0-back trials immediately preceding a modality switch with vowel presented auditorily
- 5) 0-back trials immediately following a modality switch with vowel presented auditorily
- 6) All other 0-back trials with vowel presented auditorily
- 7) 1-back trials immediately preceding a modality switch with vowel presented visually
- 8) 1-back trials immediately following a modality switch with vowel presented visually
- 9) All other 1-back trials with vowel presented visually
- 10) 1-back trials immediately preceding a modality switch with vowel presented auditorily
- 11) 1-back trials immediately following a modality switch with vowel presented auditorily
- 12) All other 1-back trials with vowel presented auditorily
- 13) 2-back trials immediately preceding a modality switch with vowel presented visually
- 14) 2-back trials immediately following a modality switch with vowel presented visually
- 15) All other 2-back trials with vowel presented visually
- 16) 2-back trials immediately preceding a modality switch with vowel presented auditorily
- 17) 2-back trials immediately following a modality switch with vowel presented auditorily
- 18) All other 2-back trials with vowel presented auditorily

Nuisance regressors:

- 19) Participant's responses
 - 20) Instructions (2.5-s periods between the blocks and a 6-s period at the beginning of each run)
 - 21) – 26) Six movement parameters (movement along three orthogonal axes, pitch, roll and yaw)
 - 27) Blocks where the percentage of correct responses was more than three standard deviations below average
-

648 In total, 27 regressors [$3(\text{memory load}) \times 6 (\text{trial type}) + 8 (\text{nuisance}) + 1 (\text{bad blocks})$] were
649 included. The regressors were convoluted with the canonical hemodynamic response function.

650 In the second-level analysis, statistical parametric maps of individual contrasts between the n -back
651 task levels and between switch and non-switch trials were averaged across participants. Working
652 Memory regions-of-interest (WM ROIs) were constructed by drawing ROIs to cover the regions
653 demonstrating greater activity (threshold $t=5.26$, cluster size > 100 , voxel-level Familywise error
654 corrected $p < 0.05$) during the 1- and 2-back tasks than during the 0-back task. Subsequent analyses
655 were performed for all voxels within the WM ROIs.

656 **5.9. Region-of-interest analysis**

657 ROI analysis was conducted in order to study the effects of gaming in cortical regions recruited
658 more extensively by the working memory (1- and 2-back) than the control condition (0-back). WM
659 ROIs were defined as regions showing greater activity during a combination of activity during 1-
660 and 2-back than during 0-back in the whole-head analysis. The WM ROIs were drawn manually
661 using Freesurfer software, and their exact locations were extracted using xjView toolbox
662 (<http://www.alivelearn.net/xjview>). Two types of repeated measures ANOVA was conducted for
663 mean signal changes within the WM ROIs. First, an ANOVA with ROI and Memory Load as
664 within-subject variables, Age Cohort and Gender as between-subjects factors, and Gaming Score,
665 DA Score and GPA as covariates was conducted. The purpose of this ANOVA was to study
666 whether gaming is associated with ROI activity, and how this might interact with task difficulty and
667 ROI location. This ANOVA was also repeated separately for switch and non-switch trials, in order
668 to examine whether any gaming-related significant effects from the first ANOVA applied
669 exclusively to either trials following a modality switch, or to non-switch trials. A second type of
670 repeated measures ANOVA was then conducted where only non-switch trials were included, and
671 Modality (visual and auditory) was added as a within-subjects variable. Similarly to the first
672 ANOVA, ROI and Memory Load were included as within-subject variables, Age Cohort and
673 Gender as between-subjects factors, and Gaming Score, DA Score and GPA as covariates. The
674 purpose of this ANOVA was to study how the modality of the presented letter might affect any
675 observed relationship between gaming and ROI activity. Switch trials were not included in this
676 ANOVA in order to minimize any “spill-over” effects in the fMRI data resulting from a recent
677 modality switch. Partial correlations (controlling for Age Cohort, Gender, DA Score and GPA)
678 were calculated between task performance and activity in the WM ROIs separately for the 1- and 2-
679 back tasks. Mediation analysis using the Process macro for SPSS
680 (<http://www.processmacro.org/index.html>) was used to examine possible mediating effects of
681 performance accuracy on the relationship between Gaming Score and activity in the WM ROIs

682 showing a significant correlation between task performance and activity, while controlling for Age
683 Cohort, Gender and DA Score. In the mediation analysis, 1000 bootstrap samples for bias-corrected
684 bootstrap confidence intervals was used, and a 95% confidence level was used. The grey matter
685 volume within each ROI was examined by using Freesurfer's automatic processing stream for
686 volume and thickness estimates (Reuter et al., 2012), and by subjecting the grey matter volume
687 estimates of the ROIs to a multivariate ANOVA with the between-subject factors Age Cohort and
688 Gender, and with Gaming Score, DA Score and GPA as covariates.

689 **Conflict of interest statement**

690 The authors declare that the research was conducted in the absence of any commercial or financial
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845

846 **Figure 1. The distribution of all questionnaire respondents into the Sociodigital Participation**
847 **(SDP) profiles.** The three SDP profiles are basic participators (blue circles), gaming-oriented
848 participators (green circles), and creative participators (green circles). Filled circles denote the
849 participants (n=167) of the current study. The data is plotted against two standardized discriminant
850 functions: Gaming activity (i.e., playing various genres of computer games, online gaming activity
851 and considering gaming as one's hobby) and Creative activity (i.e., sharing content such as videos,
852 photos or status updates online).

853 **Figure 2. Boxplots of Gaming Scores and scores for three latent gaming variables.** Gaming
854 Scores are presented separately for females and males in each of the three age cohorts **(A)**. Gaming
855 Score was defined as the sum of scores from all 10 items of the Gaming scale, probing how often
856 the participants play 10 different types of computer and video games on a 7-point response scale
857 (1=never, 2=a few times a month, 3=monthly, 4=weekly, 5=daily, 6=multiple times a day, 7=all the
858 time). Scores for the three latent variables extracted from all 10 items of the Gaming Scale **(B)**, with
859 data pooled across all participants. The three latent gaming variables were labeled Serious Games,
860 Fun Games and Sports Games. Each boxplot has lines at the lower quartile, median, and upper
861 quartile values, and the whiskers show the extent of data. Outliers (>1.5 times the interquartile
862 range) are marked with crosses.

863 **Figure 3. Associations between task performance and Gaming Score.** The difference in **(A)** the
864 percentage of correct responses and **(B)** response times between 2-back and 1-back tasks, and the
865 difference in **(C)** response times following a modality switch between 2-back and 1-back tasks is
866 plotted against Gaming Score. The data in all figures are adjusted for Age cohort and Gender. The
867 fitted regression slope (a bright red line) and 95% confidence interval bounds (light red lines) are
868 shown in each figure.

869 **Figure 4. Whole-head and region-of-interest fMRI results of cortical regions related to**
870 **working memory. A)** Cortical regions showing greater activity during a conjunction of 2-back and
871 1-back activity than during 0-back (i.e., WM ROIs; voxel-wise height threshold $t=5.26$, cluster size
872 > 100 , voxel-level Familywise error corrected $p < 0.05$). **B)** Standardized beta values for Gaming
873 Score produced by the General Linear Model (GLM) for activity in each of the WM ROIs (while
874 controlling for Age Cohort, Gender, DA Score and GPA). The activity values used in the GLM
875 represent subtractions between 1- and 0-back (left), 2- and 0-back (middle) and 2- and 1-back
876 (right) conditions. Significant beta values for the Gaming Score are indicated with asterisks (*
877 $p < 0.05$). Error bars represent 95% confidence intervals. (LH = left hemisphere, RH = right
878 hemisphere, MFG = middle frontal gyrus, SPL = superior parietal lobe, Prc = precuneus, SFG =
879 superior frontal gyrus, SMA = supplementary motor area, prefix r = right hemisphere, prefix l = left
880 hemisphere)

881 **Figure 5. The experimental setup of the *n*-back task.** Illustration of the *n*-back task showing six
882 trials of the 2-back condition including one vowel matching with a vowel delivered 2 trials back.