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Training of fluid and crystallized intelligence: A game-based approach in adolescents presenting with below average IQ

Mathilde Neugnot-Cerioli[1,2], Charlotte Gagner[1,2] and Miriam H. Beauchamp[1,2]*

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*Corresponding author: Miriam H. Beauchamp, Department of Psychology, University of Montreal, C.P. Succursale Centre-Ville, Montréal, Québec H3C 3J7, Canada; Ste-Justine University Hospital Research Center, Montreal, Quebec, Canada
E-mail: miriam.beauchamp@umontreal.ca

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Abstract: *Purpose:* This study aimed to determine whether two aspects of global intelligence, fluid (Gf) and crystallized (Gc) intelligence, could be improved in adolescents with below-average IQ by using a game-based cognitive intervention. *Method:* Thirty-four adolescents participated in cognitive interventions targeting either Gf (GAMEf, n = 12) or Gc (GAMEc, n = 12) or were assigned to a control group (n = 10). Interventions took place two days a week for one hour, over 8 weeks. Standard neuropsychological assessments were conducted prior to and after the intervention to measure possible improvements in Gc (using the Wechsler Scales, WISC-IV), and Gf (using the Test Of Non verbal Intelligence, TONI-4). *Results:* Adolescents in the GAMEf program improved on measures of Gf, while adolescents in the GAMEc program improved on both measures of Gc and Gf. *Conclusions:* The results indicate that individuals with below average IQ can improve their fluid and crystallized intellectual functioning through direct cognitive training using commercially available games, suggesting that intellectual functioning at this level may be more

ABOUT THE AUTHORS

The ABCs Developmental Neuropsychology Lab, established and directed by Dr Miriam H. Beauchamp, focuses on cerebral, cognitive, and social development from infancy, through childhood and adolescence. In general, the work conducted by the lab explores brain and cognitive maturation, as well as the biological and environmental factors that influence social and cognitive development. A number of projects investigate the cognitive and social outcomes of children and adolescents with brain insult, such as traumatic brain injury, autism spectrum disorders, and Tourette's syndrome. Empirical data related to these outcomes is translated into the development of cognitive and social intervention paradigms using game-based and virtual reality technology. The current project is part of our efforts to improve cognitive functioning in children with clinical difficulties via engaging tools and training. We aim to gain a better understanding of the underlying substrates of cognitive and social problems in the hope that this information will guide the development of targeted interventions for children at-risk for cognitive, social, or behavioral problems.

PUBLIC INTEREST STATEMENT

The main focus of this study consisted in creating a cognitive intervention program that targets different aspects of global intelligence, a rehabilitation domain that has long been overlooked because of its presumed stability. The GAME cognitive program was intended for adolescents presenting with below-average intelligence and targeted fluid intelligence (Gf: thinking logically and solving problems in new situations independently of acquired knowledge) and crystallized intelligence (Gc: a person's ability to use skills, knowledge, and experience). The program lasted for sixteen hours over the course of eight weeks and adolescents were assessed using psychometric tests prior to and after the intervention. Results showed that adolescents trained on Gf improved their Gf abilities and that adolescents trained on Gc improved both Gf and Gc abilities. This study calls into questions the so-called stability of intellectual functioning. This is also the first time that intellectual improvements have been identified in a population of clinical interest through direct training.

susceptible to remediation than previously thought. These findings could have direct implications for cognitive intervention and learning potential in clinical populations with below average IQ.

Subjects: Child Neuropsychology; Clinical Neuropsychology; Neuropsychological Rehabilitation; Cognitive Psychology

Keywords: cognition; intervention; intelligence; fluid reasoning; borderline intelligence

1. Introduction

Intelligence is a widely researched concept in contemporary psychology and a better understanding of this domain has significant clinical implications given the centrality of measures of intelligence in representing global cognitive functioning in both healthy and clinical populations. Recent findings have contributed to questioning the long-established notion that intellectual quotient is a stable, unmodifiable capacity (Healy, Wohldmann, Sutton, & Bourne, 2006; Moffitt, Caspi, Harkness, & Silva, 1993). In particular, cognitive intervention studies report improvements on core components of intellectual quotient (IQ) through specific training of fluid intelligence in typically functioning adults (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Mackey, Hill, Stone, & Bunge, 2011). However, little data exist on the putative benefits of cognitive training targeting intellectual functioning in clinical populations and individuals with below average cognitive abilities, who could benefit from improved reasoning skills (Passig & Eden, 2000; Soderqvist, Nutley, Ottersen, Grill, & Klingberg, 2012).

Earlier research in the domain of intellectual functioning aimed to develop a global understanding of intelligence, its underlying factors, and complex manifestations (Cattell, 1987; Gardner & Hatch, 1989; Spearman, 1923; Wechsler, 1939). The Catell–Horn–Caroll Theory of intelligence (Caroll, 1997) has emerged as one of the most influential models in this area of cognition. McGrew (2009) suggests that the taxonomy employed in this model “become the common nomenclature for describing research findings and theoretical frameworks” (p. 1). The Catell–Horn–Caroll model is based on a factor-analytic study that defines three strata of intellectual functioning and offers a comprehensive model incorporating theories elaborated by the three contributors. The highest strata, general intelligence (*g*) refers to a global function composed of the eight broad abilities that constitute the second strata (crystallized intelligence, fluid intelligence, general memory and learning, broad visual perception, broad auditory perception, broad retrieval ability, broad cognitive speediness, and processing speed). Each of these abilities is then conceptualized as being composed of more specific skills, such as induction, spelling, lexical knowledge, and so on. In Catell’s initial conceptualization of the model (1963), the two main broad abilities reported were fluid and crystalized intelligence. These abilities are still central in current models of intelligence and were therefore the focus of the current study. Fluid intelligence (Gf) is defined as thinking logically and solving problems in novel situations, independently of acquired knowledge. Crystallized intelligence (Gc) refers to the ability to use skills, knowledge, and experience. According to Catell’s Investment Theory, Gc is further defined as “a product over time of earlier fluid ability action” (Cattell, 1987, p. 94).

Gf and Gc are thought to be highly heritable (Bouchard, Lykken, McGue, Segal, & Tellegen, 1990; Cattell, 1963; Deary, Whalley, Lemmon, Crawford, & Starr, 2000; Gray & Thompson, 2004; te Nijenhuis, van Vianen, & van der Flier, 2007) and stable across the lifespan according to longitudinal studies (Deary et al., 2000). However, others have questioned the stability of Gc and Gf. Nisbett (2009), for example, argues that intelligence is not only influenced by heredity, but also by environmental and educational factors through culture (Nisbett, 2009; Turkheimer, Haley, Waldron, D’Onofrio, & Gottesman, 2003). In support of this idea, a study in both monozygotic and heterozygotic twins showed that IQ heritability is weak in impoverished socioeconomic environments, but particularly high in families with high socioeconomic status (Turkheimer et al., 2003).

As a result of the more traditional, static conception of intelligence, cognitive training was long overlooked in the domain of intellectual functioning as it was thought to be ineffective. More recent challenges to this idea have led researchers to explore improvements in intelligence through training. Jaeggi et al. (2008) reported that Gf can be improved through "far" cognitive transfer by targeting working memory abilities (WM), since these two abilities are strongly related. Although this line of investigation has been criticized because of lack of generalization to tasks other than those specifically trained in the study (Owen et al., 2010), a recent meta-analysis reviewing 20 studies of fluid intelligence interventions through working memory training showed a small (3–4 IQ points), yet significant, effect (Au et al., 2015). Even direct training of Gf appears to be an effective approach to improving intellectual functioning since cognitive interventions targeting fluid reasoning abilities have led to significant improvements in Gf (Bergman Nutley et al., 2011; Mackey et al., 2011). For example, Mackey et al. (2011) used commercially available games to remediate fluid reasoning abilities in children from low socioeconomic status families and found significant improvements on Gf.

Gc, defined as the ability to apply acquired knowledge to solve a problem, is mediated both by Gf (since individuals with higher Gf abilities tend to acquire Gc knowledge faster) and by socioeconomic status (Rindermann, Flores-Mendozab, & Mansur-Alvesb, 2010; Valentin Kvist & Gustafsson, 2008). Gc has been the focus of even fewer intervention studies compared to Gf. However, given that Gc is thought to be a better indicator of global academic performance (Deary, Strand, Smith, & Fernandes, 2007), it may constitute just as important an intervention target as Gf. Only one study has aimed to improve Gc through WM training and showed significant results (Alloway & Alloway, 2009). The same authors later showed that WM training improves both Gf and Gc (Alloway, Bibile, & Lau, 2013). To our knowledge, no intervention program has attempted to directly train Gc.

Reports that IQ can be improved through training suggest that intellectual functioning may be modifiable and encourage further investigations into potential intellectual improvements via cognitive training in targeted pediatric populations, in particular, children and adolescents with below-average intellectual functioning ($70 < IQ < 90$) and intellectual disability ($IQ < 70$). Perrig, Hollenstein, and Oelhafen (2009) argue that there are reasons to believe training could help enhance Gf in intellectually disabled individuals, although little empirical data exists to support this claim and results are non-consensual. Soderqvist et al. (2012) found significant improvements in Gf through WM training in children with intellectual disabilities; however, Van der Molen, Van Luit, Van der Molen, Klugkist, and Jongmans (2010) failed to find significant changes in a study using a similar approach. However, in the latter study, large intra- and inter-individual differences in the adolescents with intellectual disability were found and seemed to account for the finding that some individuals showed improvement on WM and transfer to Gf, while others did not (Soderqvist et al., 2012).

Given previous reports suggesting IQ may be modifiable and the clinical significance of potential improvements in IQ for individuals presenting with below-average intelligence ($70 < IQ < 90$), the aim of this study was to train both Gf and Gc using a direct approach, rather than through transfer by training WM. Youth who present with below average IQ and associated learning disabilities are ideal candidates for Gf and Gc training since they experience significant academic challenges and psychological difficulties (Emerson, Einfeld, & Stancliffe, 2010; Gigi et al., 2014; Hassiotis, Tanzarella, Bebbington, & Cooper, 2011; Herrington, 2009; Karande, Kanchan, & Kulkarni, 2008) that typically extend into adulthood (Hassiotis et al., 2008; Stolker, Heerdink, Leufkens, Clerkx, & Nolen, 2001). For their part, individuals with borderline intellectual functioning ($70 < IQ < 85$) encounter additional academic and adaptive challenges compared to those who exhibit within average intellectual functioning, but do not present with severe enough difficulties to meet formal disability criteria, and are therefore unable to benefit from adaptive and special services (MacMillan, Gresham, Bocian, & Lambros, 1998). As in the study conducted by Mackey et al. (2011), commercially available games were used in the current study to enhance the efficiency of the intervention and boost motivation and engagement in adolescent participants (Jaeggi, Buschkuehl, Jonides, & Shah, 2011). Games have previously been used in cognitive intervention and have been shown to be effective in improving language, attention, and executive functions (de Kloet, Berger, Verhoeven, van Stein Callenfels, & Vlieland, 2012; Munro, Lee, & Baker, 2008; Neugnot-Cerioli, Gagner, & Beauchamp, 2015; Rezaiyan, Mohammadi, & Fallah, 2007; Segers, Nooijen, & de Moor, 2006; Staiano, Abraham, & Calvert, 2012).

Two distinct cognitive training programs were designed, one targeting Gf (GAMEf) and the other targeting Gc (GAMEc). The main goal of this study was to (1) assess whether Gf and Gc can be successfully improved in adolescents with below average IQ via cognitive training based on commercially available games, (2) examine whether transfer occurs from one domain to another (e.g. Gf to Gc), since both factors are related to general intelligence (3) explore possible transfer from trained Gf and Gc to WM. Our hypotheses were that (1) Gf training would lead to improvements on measures of Gf, and Gc training would lead to improvements on measures of Gc; (2) transfer could occur from one domain to another (e.g. Gf to Gc); (3) transfer from Gf or Gc to WM might be observed since previous studies indicate transfer effects in the opposite direction (i.e. improvements on Gf or Gc when working memory is trained) (Alloway et al., 2013; Jaeggi et al., 2008; Kail & Salthouse, 1994). As such, this research focused on near transfer from directly training Gf or Gc, while still exploring the possibility of far transfer to WM (Barnett & Ceci, 2002).

2. Methods

2.1. Participants and setting

Adolescents between 12 and 16 years of age ($n = 34$, Mean age = 13.82 ± 1.08 years, number of males = 25, 74%) were recruited in a special education high school. The school's vocation is to educate youth who fail in the regular academic curriculum and cannot follow specialized programs oriented towards children with specific learning disabilities due to below average IQ. This school offers an individualized approach to teaching students and consequently does not follow the provincial curriculum. As such, students do not necessarily qualify for a high school diploma, but receive services and a tailored educational program, not otherwise possible in mainstream schools. Adolescents present to the school with a variety of pre-morbid diagnoses, and it is precisely this heterogeneity that characterizes the population and services provided (see Results for diagnostic information based on parental report from past medical and allied health evaluations). The inclusion criteria for participation in this study were: (a) aged 12–16 years; (b) Verbal or Performance IQ ranging between 70 and 90; (c) fluent French speaking. The exclusion criteria were: (a) both Performance and Verbal IQ below 70; (b) known history of diagnosed acquired brain injury; (c) participants who failed to complete at least 11 h of intervention out of a total of 16 h. A description of the participants appears in Table 1. The Ste-Justine Hospital Research Ethics Board approved the study and all participants and/or their parents provided written consent for participation.

2.2. Procedure

Participants were randomly assigned to either the GAME Crystallized (GAMEc, $n = 12$) or GAME Fluid (GAMEf, $n = 12$) intelligence training program, or to the control group (CG, $n = 10$), which was used to control for practice effects and potential differences found between pre and post assessments due to alternate test forms.

Research assistants were undergraduate or graduate students in neuropsychology and were formally trained to conduct standardized cognitive evaluations by a certified neuropsychologist. Two of the research assistants were additionally trained by the neuropsychologist to administer the GAME intervention programs, thus there were three qualified GAME facilitators for the study. GAME training included a familiarization and observation sessions and practice of the games included in the

Table 1. Participants' characteristics

Average IQ		Percentage of participants presenting with a specific diagnosis						
VIQ	PIQ	ADHD	Dyslexia	SLI	NVLD	Tourette's Syndrome	Anxiety	Depression
75.67 (7.96)	80.12 (13.84)	59.38%	31.25%	12.50%	3.12%	3.12%	6.25%	6.25%

Notes: Numbers in brackets represents standard deviation. ADHD = Attention deficit hyperactivity disorder, SLI = Specific language impairment, NVLD = Non verbal learning disorder.

program via a standardized intervention handbook. The handbook included detailed game descriptions, instructions, and rules, as well as targeted strategies to introduce throughout the intervention sessions for each game, such as "Have you considered all the instructions?", "Should we write down relevant information?".

To optimize participation in the study, the intervention took place in the school setting over the course of about 11 weeks. Neuropsychological assessments were conducted both before (pre-test) and after (post-test) the intervention, and after the equivalent lapse of time for the control group (Mean = 14.82, SD = 4.95 weeks, $F(2,33) = 0.75$, $p = 0.48$). Pre-tests were performed prior to group assignment, by either the research assistants or facilitators who were blind to students' medical and academic information. Only research assistants who were not involved in administering the intervention performed the post-tests and were therefore blind to group assignment, and any medical/academic information. All intervention sessions were conducted individually in the same school classroom dedicated to the intervention program. The sessions took place during school hours or immediately after the end of classes.

2.3. Measures

2.3.1. Socioeconomic status

Parents completed a sociodemographic questionnaire including information for calculating the Blishen socioeconomic status index (SES) (Blishen, Carroll, & Moore, 1987), as SES has been shown to influence intervention efficacy (Kinsella, Ong, Murtagh, Prior, & Sawyer, 1999; Taylor et al., 1999). The Blishen index uses average income and average education level associated with occupations in Canada (Mean = 48.04, SD = 13.71, range 21.37 (low SES) to 75.87 (high SES)).

2.4. Pre- and post-test neuropsychological measures

All tests administered during the pre- and post-test neuropsychological assessments are detailed in Table 2. In the main analyses, gold-standard test batteries were used for the assessment of intellectual functions (Gf, Gc) including the Wechsler scales and the TONI-4 (Brown, Sherbenou, & Johnsen, 2010a; Wechsler, 1999, 2003, 2006). Although the Wechsler scales (Wechsler Intelligence Scale for Children and Wechsler Abbreviated Scale for Intelligence) are not perfectly equivalent, both use the same subscale structure and the inclusion of a control group takes into account possible pre- and post-test differences. These alternate versions from the Wechsler batteries were used to minimize practice associated with presenting exactly the same items at pre- and post-test. For exploratory analyses, measures of visual and verbal working memory were included from the Wechsler scales to test possible transfer effects from Gc/Gf to working memory, given reports of transfer in the opposite direction (Alloway & Alloway, 2009; Jaeggi et al., 2008). Measures of receptive vocabulary on the Peabody Picture Vocabulary Test (PPVT) (Dunn & Dunn, 2007) and verbal fluency (Delis, Kaplan, & Kramer, 2001) were also included because of the presence of language components in the GAMEc program.

2.5. GAME intervention program

Five commercially available computerized and non-computerized games were used in both the GAMEf and GAMEc programs. Overall time spent on each game was equivalent in GAMEf (Mean = 142.50, SD = 20.11 min, $F(4,49) = 0.12$, $p = 0.97$) and GAMEc (Mean = 149.33, SD = 19.59 min, $F(4,54) = 1.16$, $p = 0.34$). For both interventions, a standardized handbook describing the intervention details and administration was developed to ensure uniformity of intervention sessions. Each adolescent was given a personal intervention notebook in which the training details were recorded by his/her facilitator: time spent on each game, levels reached and succeeded or failed, new words or concepts learned.

In GAMEf, five games with an increasing level of difficulty and eliciting deduction, planning, step-by-step and integrative reasoning were used (see Table 3 for details). The choice of games for the GAMEf program was based on the games used by Mackey et al. (2011) who reported positive

Table 2. Neuropsychological tests administered at pre and post-intervention

Domain	Pre-test	Post-test	Task
Fluid intelligence	TONI-4—Form A	TONI-4—Form B	Completing visual matrices in a test with two equivalent forms
Fluid intelligence	WISC-IV—PRI	WASI—PIQ	Completing visual matrices (matrix reasoning) and assembling blocks (blocks) to reproduce a template
Crystallized intelligence	WISC-IV—VCI	WASI—VIQ	Answering questions about lexical knowledge and assessing verbal elaboration (vocabulary) and verbal abstraction (similarities)
Receptive lexical knowledge	PPVT—Form A	PPVT—Form B	Pointing to the image corresponding to a word or concept among different images
Verbal fluency and executive functions	D-KEFS—Verbal fluency, form A	D-KEFS—Verbal fluency, form B	Producing as many words as possible from a given letter, category, or switching from one category to another within 60 s
Verbal working memory	WISC-IV—Digit span subtest	WISC-IV—Digit span subtest	Repeating a sequence of numbers forward then backward
Visual working memory	WNV—Visual span subtest	WNV—Visual span subtest	Reproducing a spatial sequence of moves on blocks forward then backward

Abbreviations: DKEFS = Delis-Kaplan executive functions system (Delis et al., 2001); PPVT = Peabody picture vocabulary test 4th edition (Dunn & Dunn, 2007); TONI-4 = Test of non-verbal intelligence, 4th edition (Brown et al., 2010a); WASI = Wechsler abbreviated scale of intelligence (Wechsler, 1999); WISC-IV = Wechsler intelligence scale for children, 4th edition (Wechsler, 2003).

Table 3. Games used in GAME-fluid and GAME-crystallized intervention programs

GAME-fluid		GAME-crystallized	
Game	**Function**	**Game**	**Function**
Tilt by ThinkFun	Planning, inhibition, fluid reasoning	Vocabulon by Megableu	Receptive vocabulary, verbal elaboration
Chocolate-Fix by ThinkFun	Inhibition, fluid reasoning, integration	Defin'Images by McWiz	Word generation
Utopia Brain Teaser by Popular Playthings	Planning, inhibition, fluid reasoning, 3D visualization	P'tit Bac by Playbac	Mental imaging, word generation, verbal elaboration
Azada (MacOs) by BigFish	Fluid reasoning	WordsWorth (MacOs) by 99 games	Word generation (reading and writing)
Pr. Layton (Nintendo3DS) by Nintendo	Fluid reasoning to solve enigmas	Adi Français (Nintendo3DS) by Ninetendo	Grammar and syntax concepts, verbal elaboration

intervention effects on fluid intelligence. The games were either the same or the constructs measured were equivalent. When participants failed to complete a level, the facilitator gave specific cues or feedback that were standardized in the facilitator's handbook and were recorded in the participant's notebook (e.g. "take your time", "read ALL the instructions", and so on). Every failed level was recorded for each game in the participant's notebook and was administered again at the next session.

In GAMEc, five games eliciting verbal fluency, receptive vocabulary, verbal elaboration, grammar and syntax concepts, and written language were used (see Table 3 for details). The selection of games for the GAMEc was more exploratory since this program constitutes a novel contribution to the cognitive rehabilitation literature. Two neuropsychologists involved in the project chose the games to reflect Cattell's definition of crystallized intelligence (Cattell, 1963), and reviewed each game before making a final common decision. None of the games used in either the GAMEc of GAMEf intervention program were similar in form or content to the standardized assessment tools used for pre- and post-neuropsychological assessment.

Both GAME programs were designed to last for 16 h over 8 weeks, with two one-hour sessions per week. However, due to holidays and school days missed for health or other reasons, the participants in this study were seen over the course of 10 to 11 weeks. Attendance ranged from 11 to 16 h (Mean = 13.71, SD = 1.08) and did not differ between groups (Mean = 13.50, SD = 0.80 in GAMEf, Mean = 13.92, SD = 1.31 in GAMEc, $F(1,23) = 0.88$, $p = 0.36$). Although facilitators monitored time spent on each game, participants were given the liberty of choosing the order in which they would play non-computer games within the session, in order to maximize positive interactions and motivation. Computer games were consistently played at the end of each session since they were perceived as more rewarding by adolescents. The games for each session were selected so that they would be played at least once every two sessions and so that overall time spent on each game was the same at the end of training.

2.6. Statistical analyses

Baseline levels of age, SES, Gf, and Gc were compared across the three groups (GAMEf, GAMEc, and control group (CG)) to ensure that results were not attributable to initial group differences.

To account for performance differences between pre-tests and post-tests, a difference score was calculated for each test by subtracting performance at pre-test from performance at post-test. ANOVAs were then performed on the difference scores for the main variables of interest (TONI-4, Verbal IQ, Perceptive IQ) across groups (GAMEf, GAMEc, CG). Dunnet's *post hoc* tests were then performed to determine the nature of any group differences. Improvement on each task was calculated by subtracting the difference scores on each task for both experimental groups (GAMEf and GAMEc) from the CG difference score. As the two versions of the Wechsler scales (WISC-IV and WASI) are not completely equivalent, it was not expected that both pre- and post-tests results would be exactly the same, in which case, the difference score for CG would be 0. Regarding the TONI-4, the same process was used since both versions (A and B) of the subtests are not perfectly correlated ($0.67 < r < 0.89$) (Brown, Sherbenou, & Johnsen, 2010b).

Exploratory ANOVAs were performed on all secondary variables including verbal WM (Digit Span forward and backward), visual WM (Visual Span forward and backward), receptive lexical knowledge (PPVT) and verbal Fluency (DKEFS verbal fluency Letters, Words, Switching, and Switching accuracy) to test possible transfer effects from Gf to working memory and from Gc to language and fluency. Dunnet's *post hoc* tests were then performed to determine the nature of any significant differences identified.

3. Results

Participants' demographic and diagnostic information is presented in Tables 4 and 5. Groups were comparable on SES and all cognitive measures at pre-test; however, a significant group difference was found for age. Participants in GAMEf were significantly older than participants in the control group (see Table 5). We performed a sensitivity analysis by using age as a covariate in all analyses and the significance of the results was the same, so we present here the original ANOVAs.

3.1. Main analyses: Group comparisons on GAME intervention difference scores

ANOVAs performed on pre- and post-test difference scores for the main variables showed a main effect of group for VIQ ($F(2,33) = 9.8.50$, $p = 0.001$) and TONI-4 ($F(2,32) = 5.90$, $p = 0.005$), but no group differences were found for PIQ ($F(2,33) = 0.19$, $p = 0.83$) (see Table 6). Dunnet post-hocs revealed that after following GAMEf, adolescents demonstrated improved scores on the TONI-4 compared to the CG, with a gain of 8.32 IQ points, while VIQ was equivalent between GAMEf and CG. Following GAMEc, adolescents demonstrated improvements on VIQ, with a gain of 8.75 IQ points compared to CG. Somewhat surprisingly, the GAMEc group also showed improvements on the TONI-4 compared to the CG, with a gain of 9.08 points (see Figure 1). The improvement scores here are calculated based on the difference between the GAMEc or the GAMEf group and CG.

Table 4. Distribution of diagnoses per participant group, percentage (number of participants)

Diagnosis	GAME-fluid	GAME-crystallized	GAME-control	χ^2
Attention deficit hyperactivity disorder	50.00% (6)	66.67% (8)	50.00% (5)	χ^2 (2, N = 34) = 3.00, p = 0.22
Dyslexia	0.00% (0)	41.67% (5)	50.00% (5)	χ^2 (2, N = 34) = 6.00, p = 0.20
Specific language impairment	16.67% (2)	8.33% (1)	20.00% (2)	χ^2 (2, N = 34) = 6.00, p = 0.20
Non verbal learning disorder	8.33% (1)	8.33% (1)	10.00% (1)	χ^2 (2, N = 34) = 3.00, p = 0.22
Tourette's syndrome	8.33% (1)	0.00% (0)	10.00% (1)	χ^2 (2, N = 34) = 6.00, p = 0.20
Dyspraxia	16.67% (2)	8.33% (1)	30.00% (3)	χ^2 (2, N = 34) = 6.00, p = 0.20
Anxiety	0.00% (0)	0.00% (0)	20.00% (2)	χ^2 (2, N = 34) = 3.00, p = 0.22
Depression	8.33% (1)	0.00% (0)	10.00% (1)	χ^2 (2, N = 34) = 6.00, p = 0.20

Table 5. Comparison of main variables between groups at pre-test

	GAME-fluid		GAME-crystallized		Control group		ANOVA	*p*-value
	Mean	SD	Mean	SD	Mean	SD		
Age	14.29	0.9	13.94	1.18	13.1	0.82	F(2,33) = 4.09	**0.03**
SES Blishen parents	41.97	13.65	52.02	14.97	45.85	10.86	F(2,27) = 1.14	0.26
Verbal IQ	75.83	7	79.25	9.21	73.8	5.45	F(2,33) = 3.50	0.27
Performance IQ	80.17	14.46	78.75	15.25	82.7	12.52	F(2,33) = 0.12	0.81
TONI-4	94.18	7.29	95	15.01	98.6	6.57	F(2,32) = 0.51	0.61
PPVT	95.33	13.17	98.75	13.25	97.4	7.85	F(2,33) = 0.25	0.78
Verbal fluency letter	18.67	6.53	19.08	5.58	19.44	5.57	F(2,33) = 0.05	0.96
Verbal fluency category	26.75	6.89	26	7.92	25.56	4.69	F(2,33) = 0.08	0.92
Verbal fluency flexibility	8.67	2.87	8.17	1.47	9.44	2.6	F(2,33) = 0.75	0.48
Verbal fluency switching words	7.83	2.89	6.5	1.68	8.56	2.24	F(2,33) = 2.15	0.14
Verbal fluency switching accuracy	7.83	2.89	6.5	1.68	8.56	2.24	F(2,33) = 2.15	0.14

Note: Significant results are bolded.

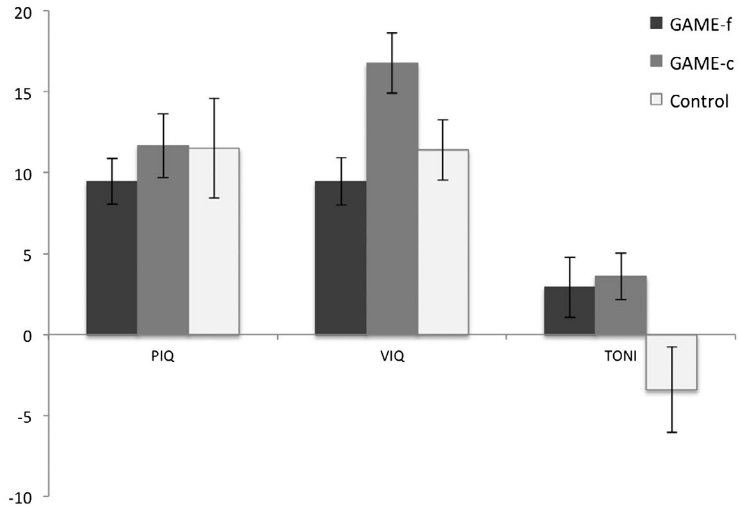
Table 6. Comparison of performance difference scores (post-test minus pre-test) for the main outcome variables

	ANOVA	Main ANOVAS		Dunnet's post-hocs							
		p-value	Effect size	Control group		GAME-crystallized		*p*-value	GAME-fluid		*p*-value
				Mean	SD	Mean	SD		Mean	SD	
VIQ	**F(2,33) = 9.77**	**<0.01**	0.39	8.8	8.35	17.58	3.48	**<0.01**	8.33	6.02	0.77
PIQ	F(2,33) = 0.21	0.81		11.5	9.7	11.67	6.85	–	9.92	4.76	–
TONI-4	**F(2,32) = 6.34**	**<0.01**	0.3	−5.5	8.37	3.58	5	0.01	2.82	5.96	**<0.01**

Note: Significant results are bolded.

Figure 1 Average difference scores between GAME-f, GAME-c and control group.

Note: Test means = 100, S.D. = 15. *$p < 0.01$.



3.2. Exploratory analyses performed on difference scores for working memory, language, and verbal fluency

No difference was found between groups on Digit Span forward ($F(2,31) = 0.68$, $p = 0.43$) and backward ($F(2,31) = 0.62$, $p = 0.55$), Visual Span forward ($F(2,32) = 0.87$, $p = 0.43$) and backward ($F(2,32) = 1.72$, $p = 0.20$), receptive vocabulary (PPVT)($p = 0.11$, $F(2,33) = 1.68$, $p = .20$) or the D-KEFS verbal fluency test for the number of words produced according to a letter ($F(2,31) = 2.10$, $p = 0.01$), a category ($F(2,31) = 0.20$, $p = 0.82$) or for switching from one category to another ($F(2,31) = 2.16$, $p = 0.13$). However, there was a significant difference on the number of correct switches (the number of times the participant switched correctly from one category to another, as opposed to the number of words belonging to both category he was able to produce) ($F(2,31) = 4.43$, $p = 0.02$). Participants in GAMEc made on average 2.50 more correct switches representing an increase of 38.46% compared to pre-test, against −0.63 in the CG ($p = 0.03$) and −0.42 in GAMEf ($p = 0.98$).

4. Discussion

The aim of this study was to assess whether two main factors of intelligence, fluid (Gf) and crystallized (Gc) intelligence, can be successfully trained in adolescents with below-average IQ associated with various learning disabilities, using cognitive intervention via commercially available games. The results indicate that direct and specific cognitive intervention targeting intelligence leads to significant improvement in both Gf and Gc. Although some prior data support the idea that Gf and Gc can be improved through working memory training (Alloway et al., 2013; Jaeggi et al., 2008), and that Gf can be altered through direct training (Mackey et al., 2011), to our knowledge, this is the first evidence that Gc can be trained directly. Until now, the limited literature addressing putative training of intellectual functions has mostly focused on normative populations and little data exists testing the modifiability of IQ in clinical populations (Soderqvist et al., 2012). It is also the first time that both Gf and Gc functions are trained in an integrated program using a comparable methodology for each.

The training targeting Gf (GAMEf) resulted in substantial improvements on a fluid-reasoning matrix task (TONI-4), showing that the training was efficient and suggesting that adolescents with below-average IQ are good candidates for direct cognitive training of Gf. No improvement was found, however, on the performance IQ scale in the GAMEf program, despite the fact that one of the subtests included in this scale is Matrix Reasoning, which is conceptually similar to the TONI-4 test. This discrepancy may be related to methodological differences between the two measures (DeThorne & Schaefer, 2004). TONI-4 may be a purer measure of Gf, while the PIQ also assesses some aspects of visual intelligence (Gv) (Chen, Keith, Chen, & Chang, 2009).

Direct training targeting Gc also shows promise for adolescents with low average IQ. Participants in this study improved substantially on the verbal IQ measure (+8.75 points compared to CG) after following the GAMEc intervention program, suggesting that Gc can also be improved through direct training with simple, commercially available games. It is particularly interesting to note that these improvements occurred in the context of a clinical population struggling in their academic curriculum. Indeed, Gc has been proven to be a good indicator of academic achievement (Deary et al., 2007) and is therefore a good target for individuals who present with learning difficulties. Of note, the program did not result in improved receptive vocabulary, suggesting that improvements in Gc measures were not simply a result of newly acquired vocabulary, but rather were related to gains in higher order cognitive processes used to reason about verbal knowledge. Verbal fluency was not affected by training in terms of retrieving words according to a given letter or category. When adolescents had to produce words by switching after each word between two categories, they all produced on average as many words. However, adolescents in the GAMEc program were more accurate in the switching portion of the tasks, while those in the control group were less competent at switching, though they produced as many words. This cognitive task necessitates both language skills as well as executive functioning and is commonly described as a more demanding task than mere categorical verbal fluency (Baldo, Shimamura, Delis, Kramer, & Kaplan, 2001; Delis et al., 2001). This improvement in GAMEc could be explained by the improvements in Gc, which may have reduced cognitive load while producing words according to two categories, and freeing cognitive resources for the executive functioning aspects of the task.

The GAMEc program also resulted in improvements on Gf as measured by the TONI-4 test, with adolescents showing better performance at post-test compared to the control group. We had not anticipated improvements across intelligence domains. It is possible that training in itself and positive interaction with the facilitators had some impact on adolescents' performance during the cognitive assessment, similar to a placebo effect (Boot, Blakely, & Simons, 2011), resulting in improved Gf in the GAMEc program. However, this explanation does not support the lack of effect in the other direction, that is, no effect of GAMEf on Gc. Also, the adolescents in this study have all experienced rehabilitation targeting language, mathematics or motor functions over the course of their curriculum and have therefore previously been engaged in positive stimulating interactions, making them presumably less susceptible to facilitator effects. An alternative explanation could be that the GAMEc program was not specific enough to Gc and also unintentionally targeted Gf, though this is not likely given that there was little to no perceptual material in GAMEc and adolescents needed to use formerly acquired knowledge (e.g. elaborating definitions, word production, etc.) to resolve games. Given that both Gc and Gf are broad factors of the higher general factor of intelligence (g) (Caroll, 1997), it is logical that improvements in Gc could lead to increased Gf; however, little data on Gc training exists and no other studies to date have explored possible transfer from Gc to Gf. These data therefore need to be replicated in future work.

No improvements were found on measures of WM after participating in GAMEf or GAMEc or being part of the control group, which is not surprising since the GAME programs were not designed to target WM abilities. Once adolescents understood the instructions for the games, they did not require WM abilities to keep rules and instructions in mind, nor was WM specifically trained in any of the games used in the intervention programs. Previous studies in cognitive training have shown cognitive transfer in the opposite direction [from WM abilities to Gf and Gc, (Alloway & Alloway, 2009; Au et al., 2015)]. The current results suggest that this relationship may be unidirectional. It has been shown that working memory training improves the ability to focus attention (Lilienthal, Tamez, Shelton, Myerson, & Hale, 2013), and Gray and Thompson (2004) suggest that WM and *g* are primarily related through attentional control processes. However, since our program did not target attention it is likely that the improvements on Gf reflect a direct effect of the GAME programs.

Overall, this study contributes to mounting evidence that Gf and Gc are not as stable as was once thought (Alloway, 2010; Alloway et al., 2013; Au et al., 2015; Diamond, Barnett, Thomas, & Munro, 2007; Jaeggi et al., 2011). As shown here, changes in IQ are not exclusive to normative populations and can be extended to clinical populations such as adolescents with below-average IQ associated with learning disabilities. This has important implications for the services and remediation offered to children and adolescents with academic difficulties. Improving intellectual functioning in these groups may lead to better vocational outcomes and consequently higher SES and quality of life in adulthood (Hunter & Schmidt, 1996).

The training programs developed in this study relied on using commercially available board games, video, and computer games and yielded promising improvements. The use of games in cognitive interventions has gained popularity in recent years (Brennan & Ireson, 1997; Craig, 2006; Segers et al., 2006) and is particularly interesting in pediatric settings. Studies have shown that their use under professional supervision can lead to improvements in various domains, such as oral and written language, attention, executive functions, and reasoning (Neugnot-Cerioli et al., 2015). Games are both ludic and motivating for children and adolescents while being effective and easy to administer. Their affordability and accessibility are particularly interesting since they can be used in many different settings, such as school, hospital, private practice or at home.

6. Limitations and avenues for future research

Despite encouraging results for the GAME intervention programs, some study limitations deserve discussion. First, the sample size for this study was relatively small and participants presented with heterogeneous conditions and comorbidities (dyslexia, ADHD, dyspraxia, etc.), which reduced the power of the statistical analyses performed. However, groups were comparable on all baseline factors except age, and the effects remained after controlling for this, leading to significant results found with large effect sizes. Future research could focus on understanding how the GAME program applies to the specific conditions encountered in this sample. Second, it was not possible to determine whether some games were more effective than others within each GAME program because it was conceived as a comprehensive intervention. It is possible that some games were less effective from a cognitive perspective; however, these may have been useful in influencing overall engagement and motivation. Third, it is unclear whether the significant cognitive gains observed during the study will remain in the long term. Future work should seek to include GAME booster sessions and systematic evaluation of long-term effects. Future studies could also focus on exploring possible broader effects of the intervention program, for example, on academic results. In this study, informal interviews were conducted during a debriefing sessions at the end of the program and students frequently reported statements of increased confidence, such as "I encounter greater success in my school evaluations now, before the program I used to think my answers would be wrong, while now I know they may not be, so I take a chance and answer", or "Now I take my time before trying to solve a problem, like we practiced together, so I avoid making the mistakes I used to make before". However, no formal, quantitative measure of self-esteem or self-confidence was administered. Finally, training sessions took place between early morning to mid-afternoon which may have influenced the results, but the sample size here did not allow to observe specifically whether or not time of day may have had an effect.

7. Conclusions

Overall, this study supports existing work in typically developing individuals suggesting that intelligence can be improved through game-based cognitive training and extend these findings to adolescents who present with below-average IQ related to learning disabilities. The GAME program uses an innovative approach by directly training both Gf and Gc in two distinct yet comparable paradigms, and relies on commercially available games.

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Competing Interests
The authors declare no competing interest.

Author details
Mathilde Neugnot-Cerioli[1,2]
E-mail: mathilde.neugnot@gmail.com
Charlotte Gagner[1,2]
E-mail: charlotte.gagner@umontreal.ca
Miriam H. Beauchamp[1,2]
E-mail: miriam.beauchamp@umontreal.ca
[1] Department of Psychology, University of Montreal, C.P. Succursale Centre-Ville, Montréal, Québec H3C 3J7, Canada.
[2] Ste-Justine University Hospital Research Center, Montreal, Quebec, Canada.

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