1. Vock, M., Holling, H. The measurement of visuo-spatial and verbal-numerical working memory: development of IRT-based scales. Intelligence, Vol.36, 2008. pp. 161-182.
2. Vock, M.: Humboldt University of Berlin, Institute for Educational Progress, Unter den Linden 6, 10099 Berlin, Germany. Holling, H.: University of Münster, Department of Psychology, Germany. Tel.: +49 30 2093 5501; fax: +49 30 2093 5336. E-mail addresses: miriam.vock@iqb.hu-berlin.de (M. Vock), holling@psy.uni-muenster.de (H. Holling)
3. The objective of this study is to explore the potential for developing IRT-based working memory scales for assessing specific working memory components in children (8–13 years). These working memory scales should measure cognitive abilities reliably in the upper range of ability distribution as well as in the normal range, and provide a much-needed, reliable, and valid test for assessing high intellectual abilities in children. Six computer-assisted working memory tasks were administered to 172 children from regular schools and to 202 children from special schools and other institutions for the gifted. A factor analysis revealed a two-factor structure and the existence of a verbal–numerical and a visuo–spatial working memory scale. Classical item analysis and IRT analysis yielded good psychometric properties for both scales and revealed that the scales are appropriate for measuring high cognitive abilities. Both scales showed substantial and differential power for the explanation of variance in school achievement.
4. М.Вок, Х.Холлинг. Измерение визуально-пространственной и вербально-числовой рабочей памяти: разработка шкал на основе IRT.
5. Цель данного исследования – изучить потенциал развития шкал рабочей памяти, основанных на IRT, для оценки специфических компонентов рабочей памяти у детей (8-13 лет). Эти шкалы рабочей памяти должны надежно измерять когнитивные способности в верхней части распределения способностей, равно как и в средней части, и давать необходимый, надежный и валидный тест для оценки высоких интеллектуальных способностей у детей. Шесть компьютерных задач на рабочую память проводились на 172 детях из обычных школ и на 202 детях из специальных школ и организаций для одаренных. Факторный анализ выявил двухфакторную структуру и наличие вербально-числовой и визуально-пространственной шкал рабочей памяти. Классический анализ пунктов и анализ, основанный на IRT, показали хорошие психометрические свойства для обеих шкал и подтвердили, что шкалы пригодны для измерения высоких когнитивных способностей. Обе шкалы показали содержательную и дифференциальную мощность в объяснении дисперсии школьных достижений.

6. Приложения:

Table 1
Means, standard deviations, distribution properties and reliability of the scale scores

Type of task	*M*	SD	Range (theoretical maximum)	Skewness	Kurtosis	K–S-test *Z* (*p*)	α
Reading span	3.80	2.56	0–10 (11)	.24	−.79	.11 (.00)	.79
Verbal span	4.02	2.65	0–10 (10)	.17	−.87	.10 (.00)	.78
Computation span	4.54	2.32	0–10 (10)	−.13	−.58	.11 (.00)	.73
Backward digit span	3.91	2.81	0–12 (12)	.69	−.25	.15 (.00)	.81
Memory updating figural	5.50	2.97	0–14 (14)	.04	−.74	.09 (.00)	.74
Spatial WM	4.86	2.79	0–12 (13)	.29	−.56	.12 (.00)	.76

Note. K–S-test: Kolmogorov–Smirnov-test on normal distribution with correction of significance by Lilliefors.

Table 2
Factor loadings of the 70 working memory items on two factors (principal component analysis, rotation: oblimin)

WM item	Factor 1: verbal–numerical	Factor 2: visuo–spatial	WM item	Factor 1: verbal–numerical	Factor 2: visuo–spatial
RS 1	**.43**	.10	BDS 5	**.48**	.10
RS 2	**.46**	−.03	BDS 6	**.52**	.09
RS 3	**.59**	.06	BDS 7	**.50**	.12
RS 4	**.49**	−.08	BDS 8	**.49**	.12
RS 5	**.43**	.06	BDS 9	**.38**	.20
RS 6	**.65**	−.04	BDS 10	**.35**	.07
RS 7	**.43**	.11	BDS 11	**.41**	.09
RS 8	**.47**	.07	BDS 12	**.26**	.08
RS 9	**.28**	.00	MUF 1	−.05	**.43**
RS 10	**.37**	.02	MUF 2	.18	**.37**
RS 11	**.33**	−.05	MUF 3	.15	**.26**
VS 1	**.45**	.00	MUF 4	.12	**.32**
VS 2	**.50**	−.01	MUF 5	−.06	**.40**
VS 3	**.58**	−.02	MUF 6	.07	.16
VS 4	**.51**	.00	MUF 7	.11	**.22**
VS 5	**.36**	.05	MUF 8	.09	**.34**
VS 6	**.50**	.06	MUF 9	.06	**.25**
VS 7	**.53**	.03	MUF 10	.06	**.36**
VS 8	**.51**	−.09	MUF 11	.15	**.34**
VS 9	**.41**	.01	MUF 12	.08	**.32**
VS 10	**.42**	−.12	MUF 13	.16	**.22**
CS 1	**.42**	−.05	MUF 14	.10	**.23**
CS 2	**.34**	−.09	SWM 1	.04	**.31**
CS 3	**.33**	.09	SWM 2	−.10	**.53**
CS 4	**.35**	.02	SWM 3	.05	**.48**
CS 5	**.44**	.00	SWM 4	−.11	**.53**
CS 6	**.36**	.04	SWM 5	.08	**.39**
CS 7	**.51**	.01	SWM 6	.06	**.47**
CS 8	**.54**	−.03	SWM 7	−.05	**.47**
CS 9	**.21**	.06	SWM 8	−.06	**.55**
CS 10	**.49**	.00	SWM 9	.02	**.31**
BDS 1	**.21**	**.22**	SWM 10	−.06	**.47**
BDS 2	**.34**	.10	SWM 11	−.01	**.41**
BDS 3	**.50**	−.02	SWM 12	.05	**.30**
BDS 4	**.53**	.02	SWM 13	−.03	**.26**

Note. RS=Reading Span, VS=Verbal Span, CS=Computation Span, BDS=Backward Digit Span, MUF=Memory Updating Figural, SWM=Spatial Working Memory. Loadings >.20 are printed in bold.

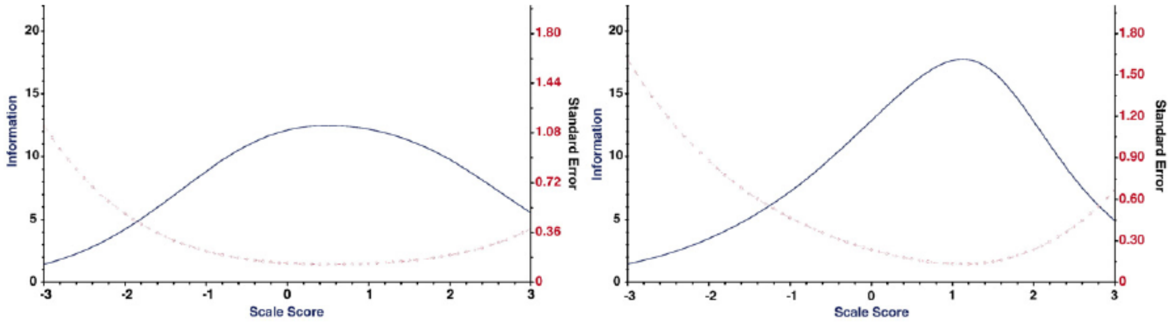

Fig. 1. Test information curve for the verbal–numerical scale, modeled by the 1PL (left figure) and the 2PL (right figure) model. Note. Regular line = text information; dotted line = standard error.

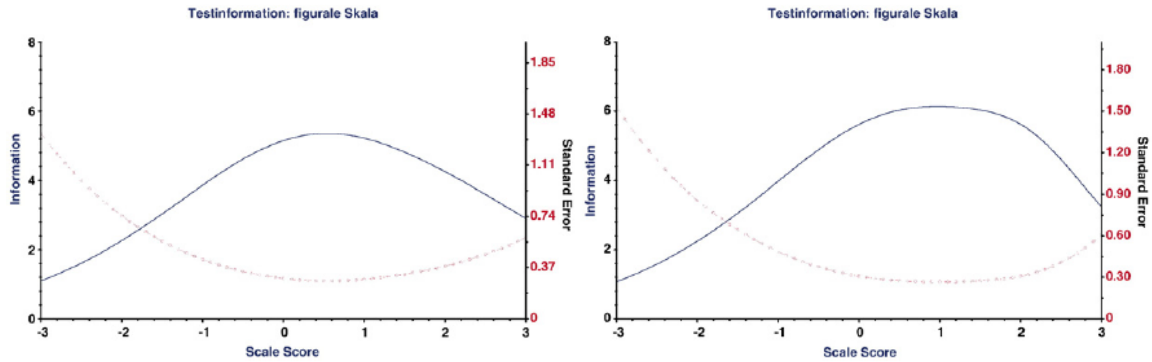

Fig. 2. Test information curve for the visuo–spatial scale, modeled by the 1PL (left figure) and the 2PL (right figure) model. Note. Regular line = text information; dotted line = standard error.

Table 3
Likelihood ratio test by Martin-Löf for both scales with the split criteria "Type of task", "Number of item" and "Difficulty of item"

Split criterion	Group 1	k_1	Group 2	k_2	χ^2	*df*	*p*
Verbal–numerical scale							
Type of task: content	Verbal tasks	21	Numerical tasks	22	384.84	461	1.00
Type of task: structure	RS/CS	21	VS/BDS	22	339.80	461	1.00
Number of item	Even	21	Odd	22	199.27	461	1.00
Difficulty of item	$\sigma_{1PL} < .65$	22	$\sigma_{1PL} \geq .65$	21	252.33	461	1.00
Visuo–spatial scale							
Type of task	MUF	14	SWM	13	274.11	181	.00
Type of task (reduced scale)	MUF	12	SWM	10	196.00	119	.00
Number of item	Even	13	Odd	14	146.94	181	.97
Difficulty of item	$\sigma_{1PL} < .72$	15	$\sigma_{1PL} \geq .72$	12	116.82	179	1.00

Note. "Type of task: structure": the structurally equivalent tasks RS and CS are compared with the other two verbal–numerical tasks BDS and VS. "Difficulty of item": separates the scale into items with a difficulty parameter in the 1-PL model above and below the scale mean.

Table 4
Likelihood ratio test by Andersen for both scales with the split criteria "Score", "Sex", "Age" and "IQ"

Split criterion	*N*	Group 1	n_1	Group 2	n_2	χ^2	*df*	*p*
Verbal–numerical scale								
Score (median)	371	High	177	Low	194	124.67	42	.00
Sex	370	Female	168	Male	202	42.58	42	.45
Age (median)	371	< 11.4 years	185	> 11.4 years	186	51.56	42	.15
IQ (CFT-20)	371	≥ 120	169	< 120	202	84.25	42	.00
Visuo–spatial scale								
Score (median)	372	High	180	Low	192	22.89	26	.64
Sex	371	Female	168	Male	203	33.82	26	.14
Age (median)	372	< 11.4 years	184	> 11.4 years	188	26.16	26	.45
IQ (CFT-20)	372	≥ 120	170	< 120	202	29.08	26	.31

Table 5
Concurrent validity of working memory scales for different ability levels: partial correlations of working memory scale scores with intelligence tests (raw test scores, age controlled)

Working memory scales	CFT-20 (fluid intelligence)	Vocabulary test	Number series completion test
All subjects (N = 374)			
Verbal–numerical score	.56*	.59*	.57*
Visuo–spatial score	.61*	.44*	.57*
High ability subjects (IQ = 120, N = 170)			
Verbal–numerical score	.35*	.41*	.44*
Visuo–spatial score	.27*	.22*	.41*
Low ability subjects (IQ < 120, N = 204)			
Verbal–numerical score	.33*	.53*	.43*
Visuo–spatial score	.56*	.36*	.48*

Note. *$p < .01$.

Table 6
Concurrent validity and incremental validity of the working memory scales for different school types and ability groups; R^2 and R^2 increments from the regression analyses of school grades on test scales

Working memory scales/intelligence tests	German		Math		Science		Grade point average	
	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2
Elementary school (n=114)								
Verbal–numerical WM (WMvn)	.31		.20		.21		.36	
Visuo–spatial WM (WMs)	.02		.24		.12		.16	
Fluid intelligence (gf)	.09		.25		.16		.24	
gf+WMvn (ΔR^2: compared to gf only)	.31	.22	.28	.03	.23	.07	.39	.15
gf+WMs (ΔR^2: compared to gf only)	.08	.00	.30	.05	.17	.01	.25	.01
gf+WMvn+WMs (ΔR^2: compared to gf only)	.31	.22	.32	.07	.23	.07	.39	.15
Verbal intelligence (vInt)	.32		.18		.20		.35	
vInt+WMvn (ΔR^2: compared to vInt only)	.40	.08	.24	.06	.25	.05	.46	.11
vInt+WMs (ΔR^2: compared to vInt only)	.32	.00	.33	.15	.25	.05	.41	.06
Numerical intelligence (nInt)	.06		.26		.14		.22	
nInt+WMvn (ΔR^2: compared to nInt only)	.31	.25	.32	.06	.23	.09	.40	.18
nInt+WMs (ΔR^2: compared to nInt only)	.05	.00	.36	.10	.17	.03	.25	.03
WMvn+WMs	.31		.30		.23		.38	
ΔR^2: compared to WMvn only		.00		.10		.02		.02
ΔR^2: compared to WMs only		.29		.06		.11		.22
Intelligences scales (gf+vInt+nInt)	.32		.32		.24		.40	
WMvn+WMs+all three intelligence scales (ΔR^2: compared to intelligence scales only)	.41	.09	.36	.04	.26	.02	.46	.06
Secondary school (n=260)								
WMvn	.19		.22		.15		.28	
WMs	.07		.15		.10		.13	
gf	.09		.22		.16		.19	
gf+WMvn (ΔR^2: compared to gf only)	.20	.11	.28	.06	.20	.04	.31	.12
gf+WMs (ΔR^2: compared to gf only)	.10	.01	.24	.02	.17	.01	.21	.02
gf+WMvn+WMs (ΔR^2: compared to gf only)	.20	.11	.29	.07	.29	.13	.31	.12
Verbal intelligence (vInt)	.23		.23		.33		.36	
vInt+WMvn (ΔR^2: compared to vInt only)	.28	.05	.29	.06	.34	.01	.42	.06
vInt+WMs (ΔR^2: compared to vInt only)	.24	.01	.27	.04	.34	.01	.37	.01
Numerical intelligence (vInt)	.15		.29		.22		.28	
nInt+WMvn (ΔR^2: compared to nInt only)	.22	.07	.33	.04	.24	.02	.36	.08
nInt+WMs (ΔR^2: compared to nInt only)	.15	.00	.30	.01	.22	.00	.29	.01
WMvn+WMs	.19		.25		.17		.29	
ΔR^2: compared to WMvn only		.00		.03		.02		.01
ΔR^2: compared to WMs only		.12		.10		.07		.16
Intelligences scales (gf+vInt+nInt)	.24		.33		.35		.39	
WMvn+WMs+all three intelligence scales (ΔR^2: compared to intelligence scales only)	.27	.03	.35	.02	.35	.00	.42	.03

Note. Science in elementary school: grade in the subject “Sachkunde” only. Science in secondary school: average of the grades in chemistry, physics and biology.

Table 7
Concurrent validity of the working memory scales for high and low ability students in elementary and secondary school (in comparison to the validity of intelligence tests); bivariate correlations between test scales and school grades

Working memory scales/ intelligence tests	German	Math	Science	Grade point average
Elementary school, high ability group ($IQ \geq 120$; $n = 49$)				
Verbal–numerical WM	−.57**	.00	−.25	−.41**
Visuo–spatial WM	.14	−.22	−.17	−.10
CFT-20 (fluid intelligence)	−.10	.13	.02	.01
Verbal intelligence	−.41**	.02	−.15	−.28
Numerical intelligence	−.10	−.11	−.07	−.12
Elementary school, low ability group ($IQ < 120$; $n = 65$)				
Verbal–numerical WM	−.52**	−.45**	−.42**	−.57**
Visuo–spatial WM	−.20	−.48**	−.27*	−.38**
CFT-20 (fluid intelligence)	−.24	−.46**	−.37**	−.43**
Verbal intelligence	−.60**	−.45**	−.48**	−.63**
Numerical intelligence	−.24	−.57**	−.43**	−.49**
Secondary school, high ability group ($IQ \geq 120$; $n = 121$)				
Verbal–numerical WM	−.33**	−.38**	−.25**	−.41**
Visuo–spatial WM	−.12	−.33**	−.07	−.19*
CFT-20 (fluid intelligence)	−.09	−.37**	−.12	−.19*
Verbal intelligence	−.35**	−.36**	−.37**	−.42**
Numerical intelligence	−.30**	−.50**	−.36**	−.46**
Secondary school, low ability group ($IQ < 120$; $n = 139$)				
Verbal–numerical WM	−.44**	−.39**	−.31**	−.47**
Visuo–spatial WM	−.22*	−.24**	−.30**	−.29**
CFT-20 (fluid intelligence)	−.23**	−.34**	−.37**	−.37**
Verbal intelligence	−.52**	−.50**	−.60**	−.63**
Numerical intelligence	−.32**	−.42**	−.38**	−.41**

Note. German grade point system: grades are between 1 and 6, 1 being the best and 6 the worst grade. Thus, negative correlations indicate a positive relationship between score and academic achievement. Science in elementary school: grade in the subject "Sachkunde" only. Science in secondary school: average of the grades in chemistry, physics and biology.
$^*p < .05$. $^{**}p < .01$.

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