Supplementary Material

Autistic traits in synaesthesia: atypical sensory sensitivity and enhanced perception of details

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Supplementary Figures

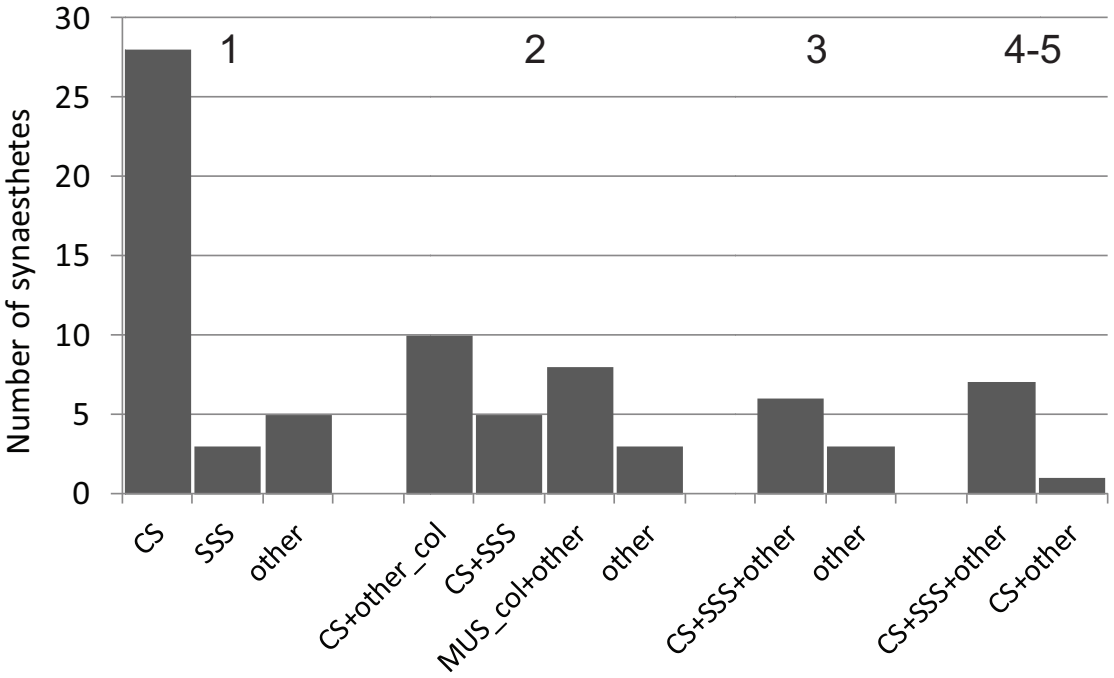

Figure S1. Types of synaesthesia in Study 1 (N=79 synaesthetes).
At the top the number of classes of synaesthesia are listed (according to Novich et al., 2011 [1]). CS = coloured sequences, SSS = sequence-space synaesthesia, other_col = other synaesthesias involving colour (e.g. coloured sensations or lexical-colour synaesthesia), MUS_col = music-colour synaesthesia.

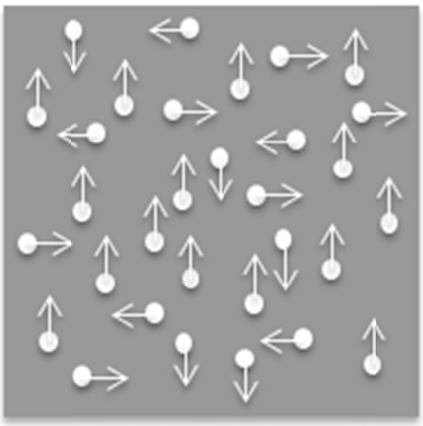

Figure S2. Schematic display of the motion coherence task. The subjects' task was to indicate the global direction of motion (left, right, up or down). Figure reproduced from Burghoorn et al. [2].

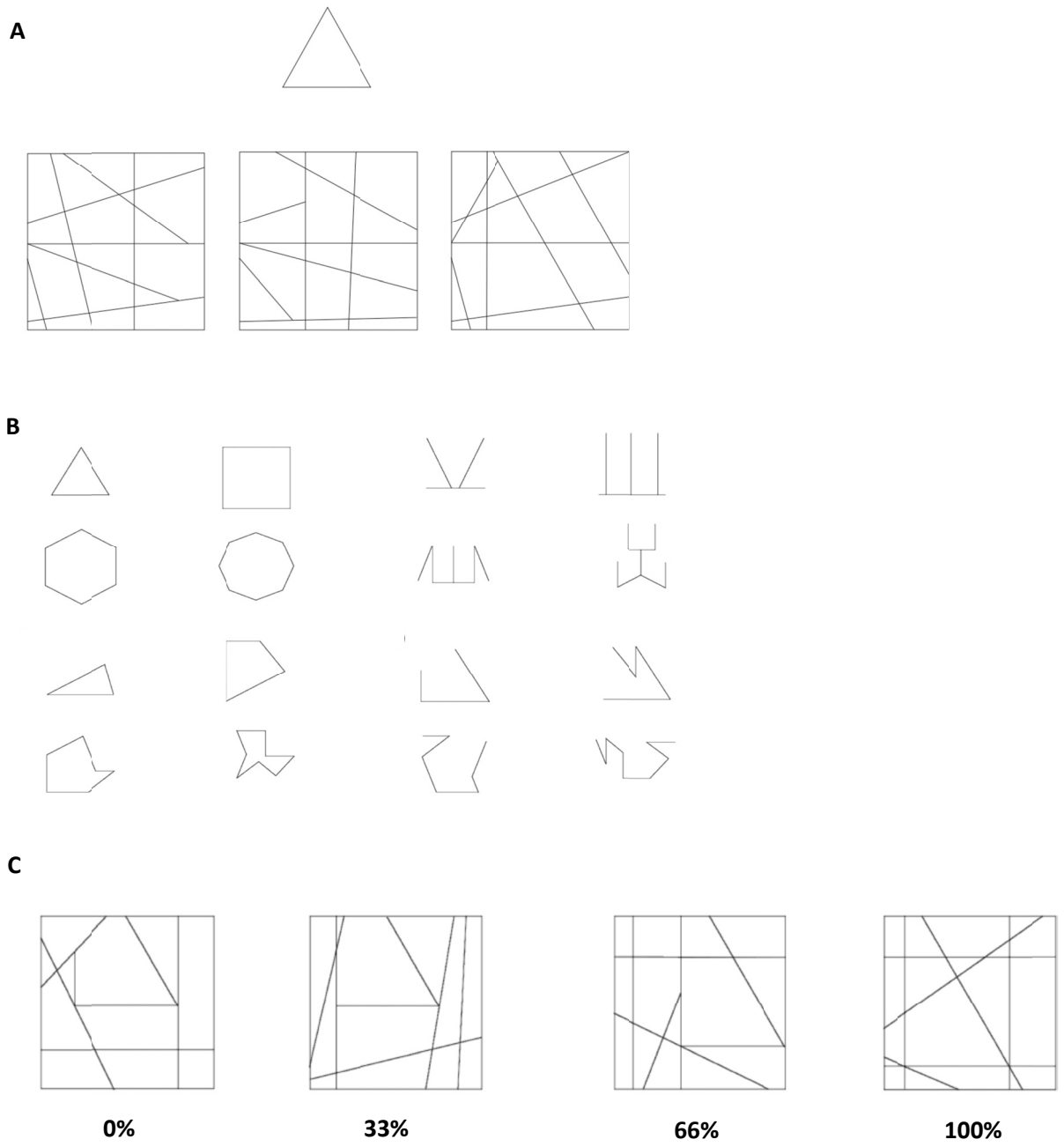

Figure S3. Examples of the stimuli and stimulus display of the embedded figures task.
A) Example of a trial display. The subjects' task was to indicate in which context display (bottom) the target figure (top) was hidden. B) The 16 target shapes. C) Embedding contexts for a target stimulus (third target on row three in B) at 4 levels of difficulty: 0%, 33%, 66% and 100% continued lines. Adapted version of Figure 1 and Figure 2 of De-Wit et al. [3] under a Creative Commons CC-BY 4.0 license.

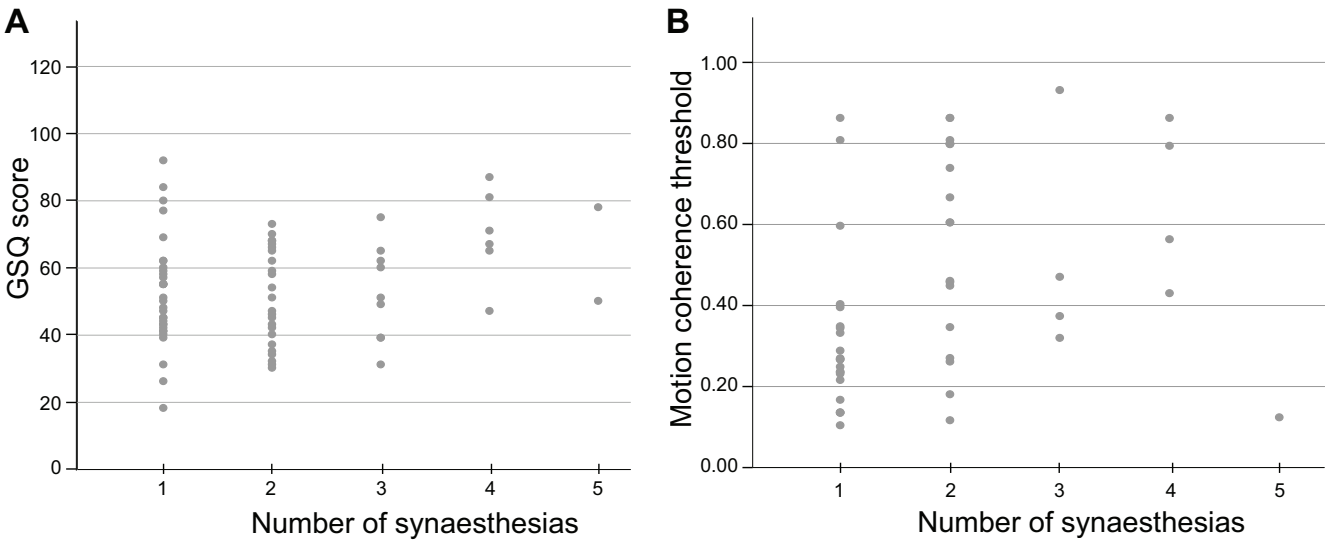

Figure S4. Dose effects of synaesthesia on the Glasgow Sensory Questionnaire (A) and the motion coherence task (B). For results see main text.

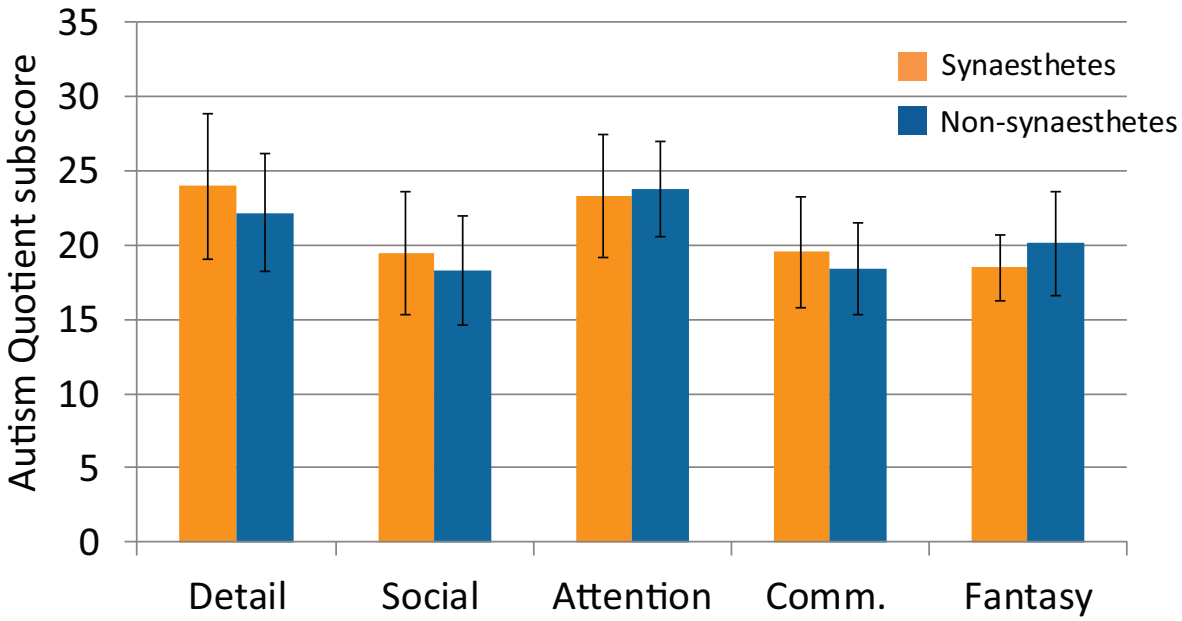

Figure S5. Autism Quotient scores for sequence-space synaesthetes (*N*=17) and matched non-synaesthetes (*N*=20) of Study 2. Detail = AQ-Attention to detail; Social = AQ-Social skills, Attention = AQ-Attention switching, Comm. = AQ-Communication. Error bars denote the standard deviation.

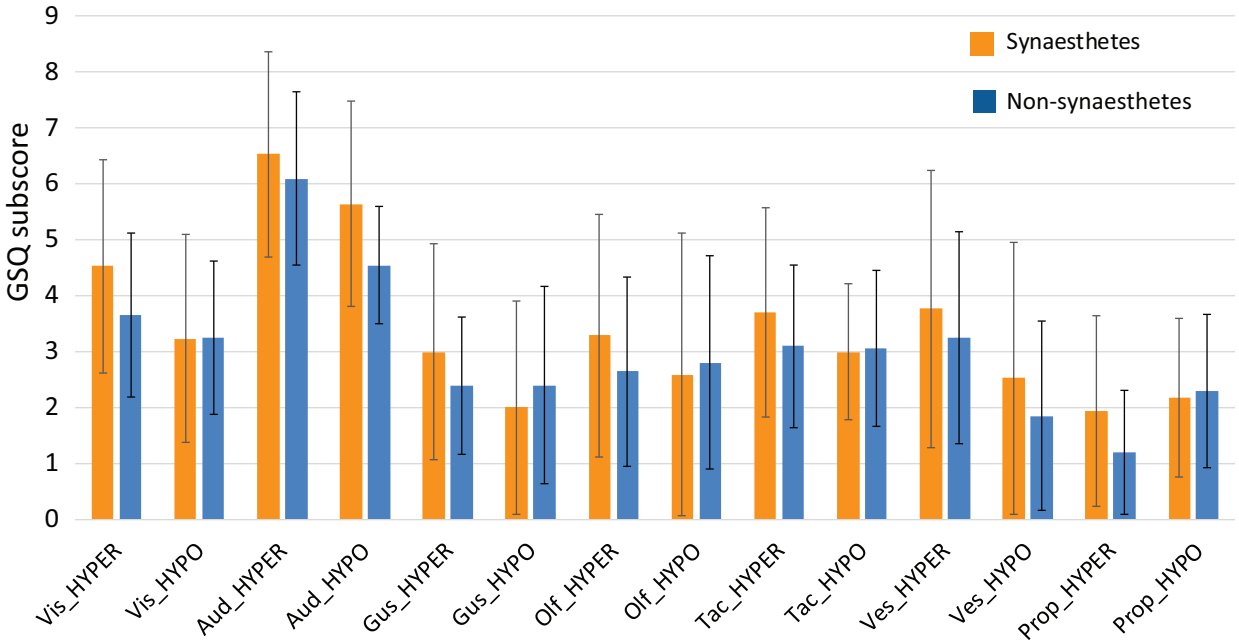

Figure S6. Average Glasgow Sensory Questionnaire subscores for synaesthetes (*N*=17) and non-synaesthetes (*N*=20) of Study 2. Vis = visual, aud=auditory, gus = Gustatory, olf=olfactory, tac=tactile, ves=vestibular, prop=proprioceptive. Error bars denote the standard deviation.

Supplementary Tables

Supplementary Table S1: *Detailed classification of synaesthesias (Study 1)*

sj nr	synesthesia labels	Novich class	Novich class	Novich class	Novich class	Novich class	Novich class	lex	tt	nr of syn
1	GCS	cs								1
2	GCS	cs								1
3	GCS	cs								1
4	MUS, Lex_Shape	cm						lex		2
5	SSS	sss								1
6	MTS	nvs								1
7	GCS	cs								1
8	GCS, SSS, TU_C, MUS, GUS	cs	sss	cs	cm	nvs				4
9	GCS, SSS, MUS	cs	sss	cm						3
10	GCS, TU_C	cs	cs							1
11	GCS, TU_C, TT	cs	cs						tt	2
12	GCS, TU_C	cs	cs							1
13	GCS, SSS, TU_C, MUS	cs	sss	cs	cm					3
14	GCS, Lex_C, TU_C	cs						lex		2
15	GCS, GUS_C	cs	csen							2
16	GCS, TU_C, GUS_C	cs	cs	csen						2
17	GCS, TU_C	cs	cs							1
18	GCS, SSS, Lex_C	cs	sss					lex		3
19	GCS	cs								1
20	GCS, SSS	cs	sss							2
21	GCS, TU_C, GR_P	cs	cs	csen						2
22	GCS	cs								1
23	GCS, SSS	cs	sss							2
24	GCS, SSS, MUS	cs	sss	cm						3
25	GCS, TU_C	cs	cs							1
26	GCS, TU_C	cs	cs							1
27	TU_C, MUS	cs	cm							2
28	SSS	sss								1
29	MUS, GUS	cm	nvs							2
30	GCS, MTS	cs	nvs							2
31	GCS, GR_P, MTS	cs	csen	nvs						3
32	GCS, TU_C	cs	cs							1
33	MUS	cm								1
34	MUS, GUS	cm	nvs							2
35	TU_C	cs								1
36	GCS, TU_C	cs	cs							1
37	Lex_C, MUS		cm					lex		2
38	GCS, TU_C	cs	cs							1
39	GCS, SSS, GR_P, MUS, GUS	cs	sss	csen	cm	nvs				5
40	GCS	cs								1
41	GCS, TU_C	cs	cs							1
42	LEX_C, EMO		csen					lex		2

43	GCS, SSS, MUS, GUS	cs	sss	cm	nvs					4
44	GCS, TU_C	cs	cs							1
45	GCS, GR_P	cs	csen							2
46	GCS	cs								1
47	GCS, TU_C	cs	cs							1
48	GCS	cs								1
49	GCS, TU_C	cs	cs							1
50	GCS, SSS, TU_C, MUS, GUS	cs	sss	cs	cm	nvs				4
51	GCS, SSS, TU_C	cs	sss	cs						2
52	Lex_GUS, MUS, Pain	nvs	cm	csen						3
53	GCS, TU_C	cs	cs							1
54	GCS, TU_C, MUS, GUS, Pain	cs	cs	cm	nvs	csen				4
55	GCS, SSS, MUS, GUS_C	cs	sss	cm	csen					4
56	Lex_C, TU_C		cs					lex		2
57	TU_C, GUS_C	cs	csen							2
58	GCS, SSS, GR_P, TU_C, MUS, Pain	cs	sss	csen	csen	cm	csen			4
59	GCS, SSS, Lex_S, MUS, GUS_C, Pain	cs	sss		cm	csen	csen	lex		5
60	GCS, SSS	cs	sss							2
61	Lex_GUS, MUS	nvs	cm							2
62	GUS_S, MTS	nvs	nvs							1
63	GCS, SSS, GR_P	cs	sss	csen						3
64	GCS, SSS	cs	sss							2
65	GCS, TU_C	cs	cs							1
66	GCS, SSS, MUS	cs	sss	cm						3
67	SSS	sss								1
68	TU_C	cs								1
69	GCS, TU_C, Pain	cs	cs	csen						2
70	GCS, MUS	cs	cm							2
71	Lex_C, TU_C		cs					lex		2
72	GCS	cs								1
73	GCS, Lex_C	cs						lex		2
74	MUS	cm								1
75	GCS	cs								1
76	TU_C, MUS	cs	cm							2
77	Lex_GUS	nvs								1
78	TU_C	cs								1
79	Lex_C, Pain, GUS_S		csen	nvs				lex		3

Abbreviations: sj nr = subject number, lex = lexical synaesthesia, tt = tickertape, nr of syn = number of unique synaesthesia classes, cs = coloured sequences, sss = sequence-space synaesthesia, cm = coloured music, csen = coloured sensations, nvs = non-visual sequela. GCS = grapheme-colour synaesthesia, MUS = music synaesthesia, MTS = mirror-touch synaesthesia, TU_C = time-unit colour, GUS_C = gustatory-colour synaesthesia, GR_P = grapheme personification, EMO = coloured emotions, Pain = coloured pain.

Supplementary Table S2: *Descriptive statistics Study 1*

Measure	**Synaesthetes**			**Non-synaesthetes**			**Statistics***
	N	*Mean(SD)*	*Range*	*N*	*Mean(SD)*	*Range*	
Age	79	36.19(15.16)	18-72	76	23.28(6.67)	18-61	***p*<.001**
Gender	79	8M/71F		76	15M/61F		*p*=.092
Synaesthesia consistency score	64	0.78(0.30)	0.19-1.38)	40	2.37(0.49)	1.27-3.23	***p*<.001**
AQ-Total	79	110.71(15.45)	70-140	76	105.99(12.16)	74-136	*p*=.126
AQ-Detail	79	26.73(5.88)	15-38	76	23.88(4.32)	14-34	***p*=.002**
AQ-Social	79	21.97(5.01)	12-35	76	19.41(4.60)	12-33	***p*=.007**
AQ-Attention	79	23.33(4.49)	14-33	76	23.03(4.16)	15-34	n.s.
AQ-Communication	79	19.97(4.20)	12-33	76	20.00(3.42)	13-30	n.s.
AQ-Fantasy	79	18.70(4.05)	11-30	76	19.67(3.35)	12-27	***p*=.025**
GSQ	74	54.31(16.67)	18-105	62	46.47(16.98)	18-104	***p*=.038**
MCT	49	0.45(0.26)	.11-.93	50	0.34(0.20)	.068-.86	***p*=.005**
EFT-Overall							
Errors (%)	44	9.33(5.56)	0.0-22	64	12.87(6.01)	1.6-25	*p*=.054
RTs (s)	44	4.71(2.25)	1.64-11	64	3.36(1.01)	1.89-6.0	*p*=.093

*For full statistics see main text. Reported p-values are for group effects. Syn. cons. score = synaesthesia consistency test score, AQ=Autism Quotient, GSQ=Glasgow Sensory Questionnaire, MCT = Motion Coherence Threshold, EFT = Embedded Figures Task, RTs = reaction times.

Supplementary Table S3: *Descriptive statistics Study 2*

Measure	**Sequence-space synaesthetes**			**Non-synaesthetes**			**Statistics***
	N	*Mean(SD)*	*Range*	*N*	*Mean(SD)*	*Range*	
Age	18	21.9(4.6)	18-38	20	21.6(1.8)	18-24	n.s.
Gender	18	16F/2M		20	18F/2M		n.s.
AQ-Total	17	104.6()	90-136	20	102.7()	84-124	n.s.
AQ-Detail	17	23.94(4.14)	17-32	20	22.15(3.64)	16-30	*p*=.23
AQ-Social	17	19.41(4.16)	11-28	20	18.25(3.64)	13-26	n.s.
AQ-Attention	17	23.29(4.16)	17-34	20	23.75(3.23)	17-30	n.s.
AQ-Communication	17	19.53(3.71)	14-25	20	18.40(3.05)	12-23	n.s.
AQ-Fantasy	17	18.47(2.18)	15-23	20	20.10(3.48)	15-27	*p*=.10
GSQ	17	47.9(19.1)	27-102	20	42.6(10.7)	20-66	*p*=.29
MCT	18	0.27(0.15)	.10-.63	19	0.39(0.18)	.04-.69	***p*=.031**
EFT-Overall							
Errors (%)	16	9.18(4.60)	3.1-18.8	18	12.67(6.36)	1.6-23.4	*p*=.079
RTs (s)	16	2.96(0.95)	1.65-6.62	18	2.72(0.93)	1.58-6.17	n.s.

*For full statistics see main text. Reported p-values are for group effects. AQ=Autism Quotient, GSQ=Glasgow Sensory Questionnaire, MCT = Motion Coherence Threshold, EFT = Embedded Figures Task, RTs = reaction times.

Supplementary Methods

Verifying (non)synaesthetes and synaesthete classification Study 1

Synaesthetes. Sixty-four out of 79 synaesthetes completed an online synaesthesia consistency test to objectively verify synaesthesia [4-6]. Sixty-three synaesthetes took a test on the website gno.mpi.nl; one completed the Eagleman Battery [5]. The remaining fifteen synaesthetes either had a form of synaesthesia that could not be verified online, e.g. mirror-touch or taste synaesthesias (*N*=7), or did not complete a test (*N*=8). These synaesthetes were included in the study on the basis of self-report and their positive answers to standard questions about synaesthesia, e.g. 'Letters always evoke a colour'.

On the website gno.mpi.nl consistency tests were available for grapheme-colour (A-Z and 0-9, 36 items), number-colour (10 items), spoken vowel-colour (16 items), days-colour (7 items), months-colour (12 items), music-colour (14 items) and Cyrillic letters-colour (16 items) synaesthesia. Every test item was presented three times in random order and participants chose the associated colour from a full colour spectrum. RGB values for the three colour choices per item were recorded and their Euclidean difference computed [5, 6]: the smaller the RGB differences, the stronger the colour consistency. Our consistency cut-off for synaesthesia was 1.43 as in Rothen et al. [6] for the 36-item grapheme-colour synaesthesia test; for tests with maximally 16 items the cut-off was more stringent (1.0) to minimize the possibility of mnemonic strategies. One synaesthete was excluded for failing to meet the cut-off. The average synaesthete consistency score was 0.78±0.30, well below the cut-off for synaesthesia.

Our samples' forms of synaesthesia are listed in Table S1. Grapheme-colour synaesthesia (*N*=59) was most predominant. Synaesthesias were assigned classes according to Novich et al. [1]: coloured sequences (e.g. grapheme-colour, time-unit colour), sequence-space synaesthesias (e.g. number lines), coloured music, coloured sensations (e.g. coloured pain, coloured taste), and non-visual sequela synaesthesias (e.g. sound-taste, mirror-touch). Classes of synaesthesia were counted for analyses of synaesthesia dose-effects [7].

Non-synaesthetes. Forty out of 76 non-synaesthetes were verified with a consistency test for grapheme-colour synaesthesia (letters A-Z, integers 0-9, via gno.mpi.nl). Nine additional non-synaesthetes completed the test but answered with 'no color' or black for all items. They were

retained in the sample but their consistency scores were not considered reliable. The remaining 27 non-synaesthetes did not complete a consistency test and were included on the basis of their negative answers to the synaesthesia screening questionnaire. One non-synaesthete scored below the 1.43 cut-off for synaesthesia on the consistency test - a score of 1.27. Because the participant indicated no subjective experience of colour for graphemes nor any other form of synaesthesia the participant was retained in the non-synaesthete sample. The mean consistency score obtained for non-synaesthetes was 2.37±0.49 which is clearly above the cut-off for synaesthesia.

Supplementary Results Study 2

Glasgow Sensory Questionnaire

For sequence-space synaesthetes, GSQ scores correlated significantly with AQ-Total, $r(17)=0.592$, $p=.012$, 95% CI [-.238, .909], but not with any AQ-subscale, although all but the AQ-Fantasy subscale ($r(17)=-0.064$, n.s.) were marginally correlated (all $r(17)$ between [0.430, 0.443], all p-values between [.075, .085]). For non-synaesthetes a correlation with AQ-Attention-to-detail was present ($r(20)=0.528$, $p=.017$, 95% CI [.123, .815], but did not survive correction for multiple comparisons; no other correlations with AQ were significant (all $r(20)$ within [-.091, 0.29], all $p>.220$).

We explored group effects with regard to the GSQ hyper/hypo sensitivity and sensory modality subscores (see Fig. S5). A repeated measures ANCOVA revealed no 3-way interaction of Sensitivity (Hyper/hypo) by Sensory modality (7 subscales) by Group ($F(6,210)<1$, n.s.) and no interaction of Group x Sensory modality ($F(6,210)<1$, n.s.). A Group x Sensitivity interaction was not significant ($F(1,35)=3.00$, $p=.092$) but revealed a tendency for SSS to score higher on hypersensitivity subscales similar to the results of Study 1. Exploration of effects on separate sensory modalities was not justified.

Motion Coherence task

For the MCT, we explored correlations with AQ and GSQ scores. For SSS, AQ-Total, AQ-Attention, and AQ-Fantasy correlated with the MCT ($r(17)=-.540$, $p=.025$; $r(17)=-.516$, $p=.034$; $r(17)=-.484$, $p=.049$, respectively) but did so negatively suggesting a low MCT is related to a high AQ, contrary to our expectations. For non-synaesthetes, the MCT correlated positively with AQ-Social ($r(19)=.520$, $p=.023$). None of the effects survived corrections for multiple comparisons.

Embedded Figures task

We explored correlations of EFT performance with AQ, GSQ, and MCT for the overall EFT error rates and overall RTs. For SSS, no significant correlations were found. For non-synaesthetes, the EFT error rates correlated negatively with the motion coherence threshold ($r(17)=-.516$, $p=.034$, 95% CI [-.825, .027]) indicating that non-synaesthetes who made less errors on the EFT also had a lower MCT. None of the other correlations were significant.

Supplementary References

[1] Novich, S., Cheng, S. & Eagleman, D. M. 2011 Is synaesthesia one condition or many? A large-scale analysis reveals subgroups. *Journal of Neuropsychology.* **5**, 353-371. (DOI:10.1111/j.1748-6653.2011.02015.x).

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[5] Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D. & Sarma, A. K. 2007 A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods.* **159**, 139-145. (DOI:10.1016/j.jneumeth.2006.07.012).

[6] Rothen, N., Seth, A. K., Witzel, C. & Ward, J. 2013 Diagnosing synaesthesia with online colour pickers: Maximising sensitivity and specificity. *Journal of Neuroscience Methods.* **215**, 156-160. (DOI:10.1016/j.jneumeth.2013.02.009).

[7] Ward, J., Brown, P., Sherwood, J. & Simner, J. 2018 An autistic-like profile of attention and perception in synaesthesia. *Cortex.* **107**, 121-130. (DOI:10.1016/j.cortex.2017.10.008).