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Versions

Unpacking the Neural Correlates of Flow

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Department of Psychology
Goldsmiths, University of London

30 September, 2020

A thesis submitted for the degree of Doctor of Philosophy.

Thesis Abstract

Acknowledgements

Author’s Declaration

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1. 2. 2. Beyond the challenge-skill balance model

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1. 3. 2. A brief note on methods of neuroimaging

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1. 3. 4. fNIRS studies on flow

1. 3. 5. EEG studies on flow

1. 3. 6. Neuroimaging studies on flow proneness

1. 3. 7. General overview of neural studies on flow

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p np nl ij ijn n pćk ijćk n ćlp l p ćk

l n l pn ćkn ćkl ćk ij ćk ćlp ppn ćk ijn l ćk l ij ćk
l ćk ij v n ij ćk ijn

Chapter 2 Neural correlates of subjective flow in musicians

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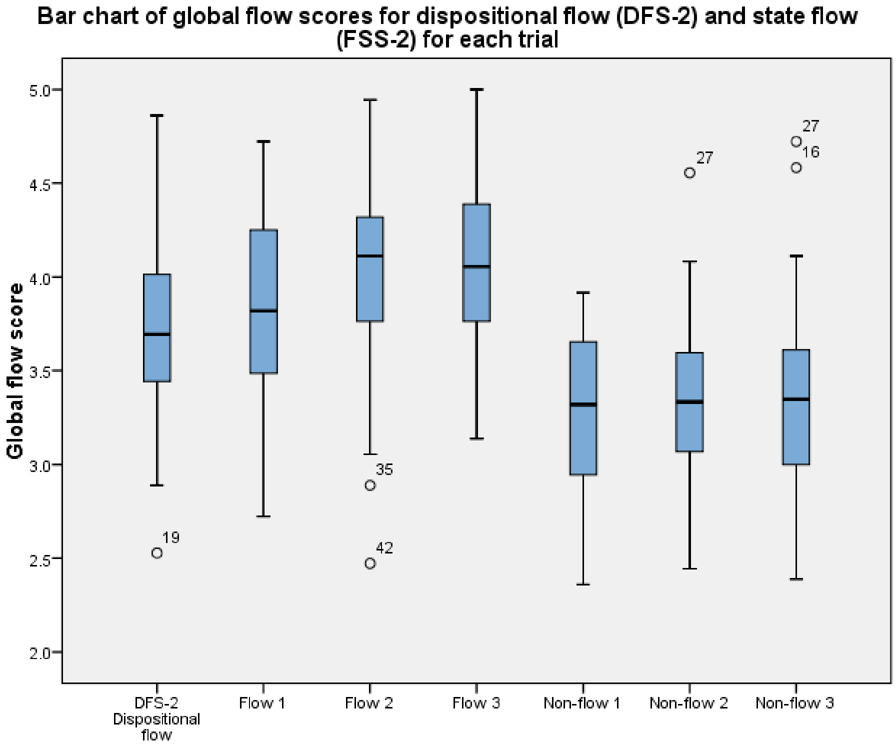
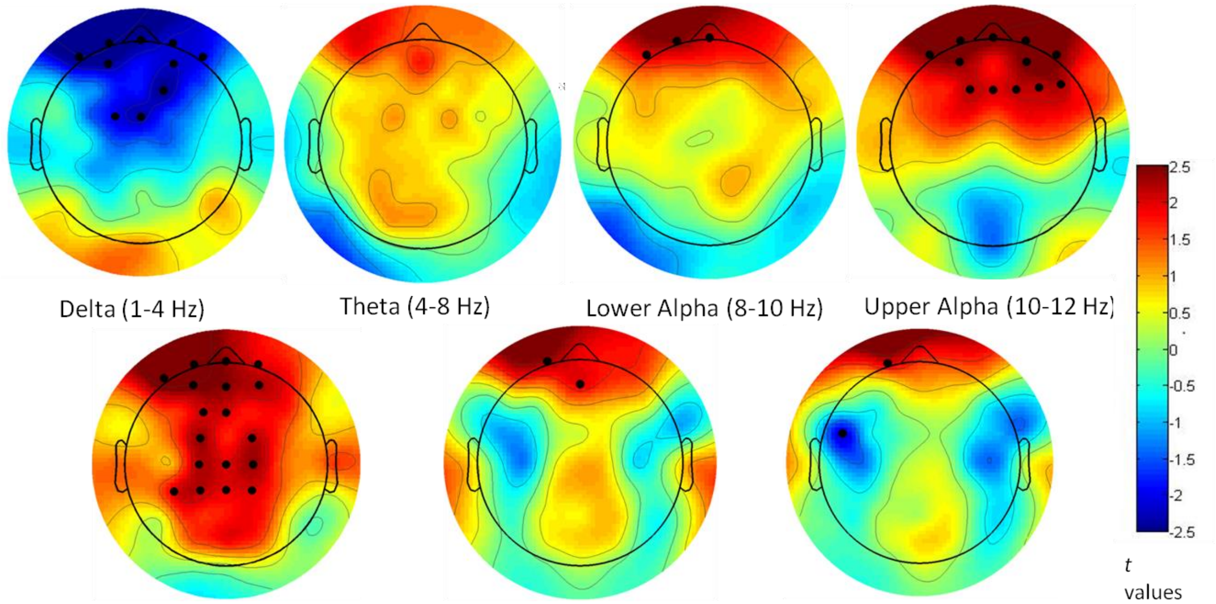


ĉk p pl p np nl ŋ ŋŋ l p ĉk ŋŋ n ĉk ŋ ŋŋ
P B ŋŋ P B l ŋŋ P B L nl ŋŋ P B
L nl ŋŋ P B l L nl ŋŋ P B l n ĉlp n
ĉk pĉkŋ ĉk n ĉk p np nl ŋ ŋŋ

2. 4. 2. Neural data

2. 4. 2. 1. Neural oscillations



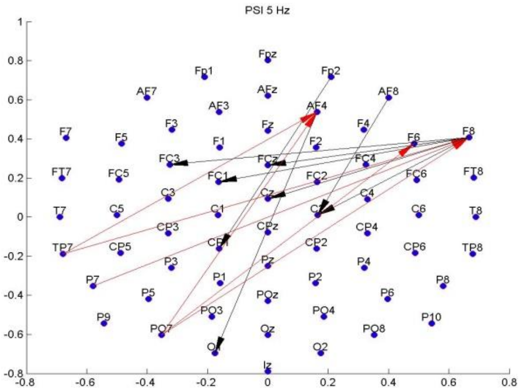
Delta (1-4 Hz) Theta (4-8 Hz) Lower Alpha (8-10 Hz) Upper Alpha (10-12 Hz)

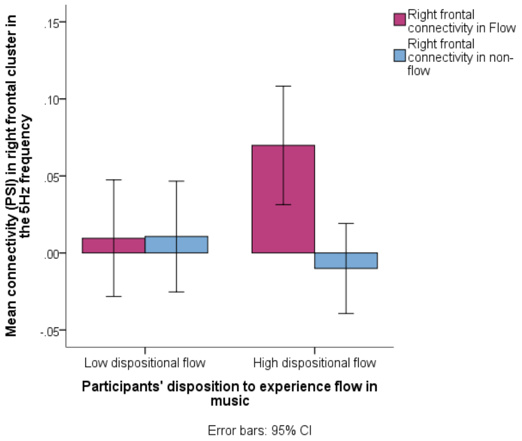
Beta (12-30 Hz) Lower Gamma (30-45 Hz) Upper Gamma (45 - 70Hz)

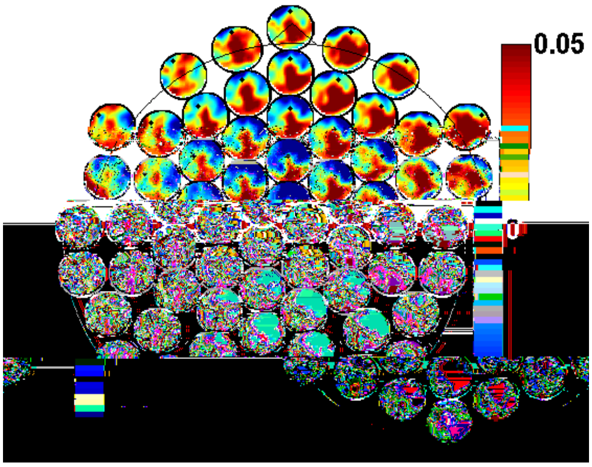
Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

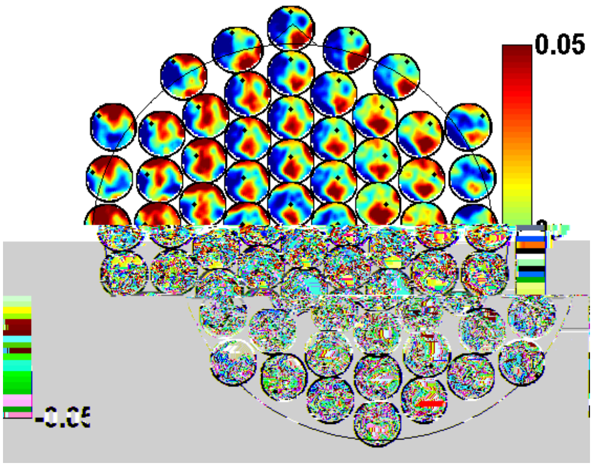
ɗk n n ijn p n l ɗk ɗkg ɗkp ɗk ij n ɗk n ijn l l nl ijn nl nl p

2. 4. 2. 2. Functional Connectivity









[illegible]

2. 5. Discussion

2. 5. 1. Behavioural data

2. 5. 2. Neural data

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Chapter 3 Differentiating enjoyment and challenge-skill balance from flow

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3. 2. Methods

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3. 2. 3. Materials

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3. 2. 6. EEG recording and analysis

3. 2. 7. Preprocessing

3. 2. 8. Time-Frequency Analysis

3. 2. 9. EEG Statistical analysis

3. 3. Results

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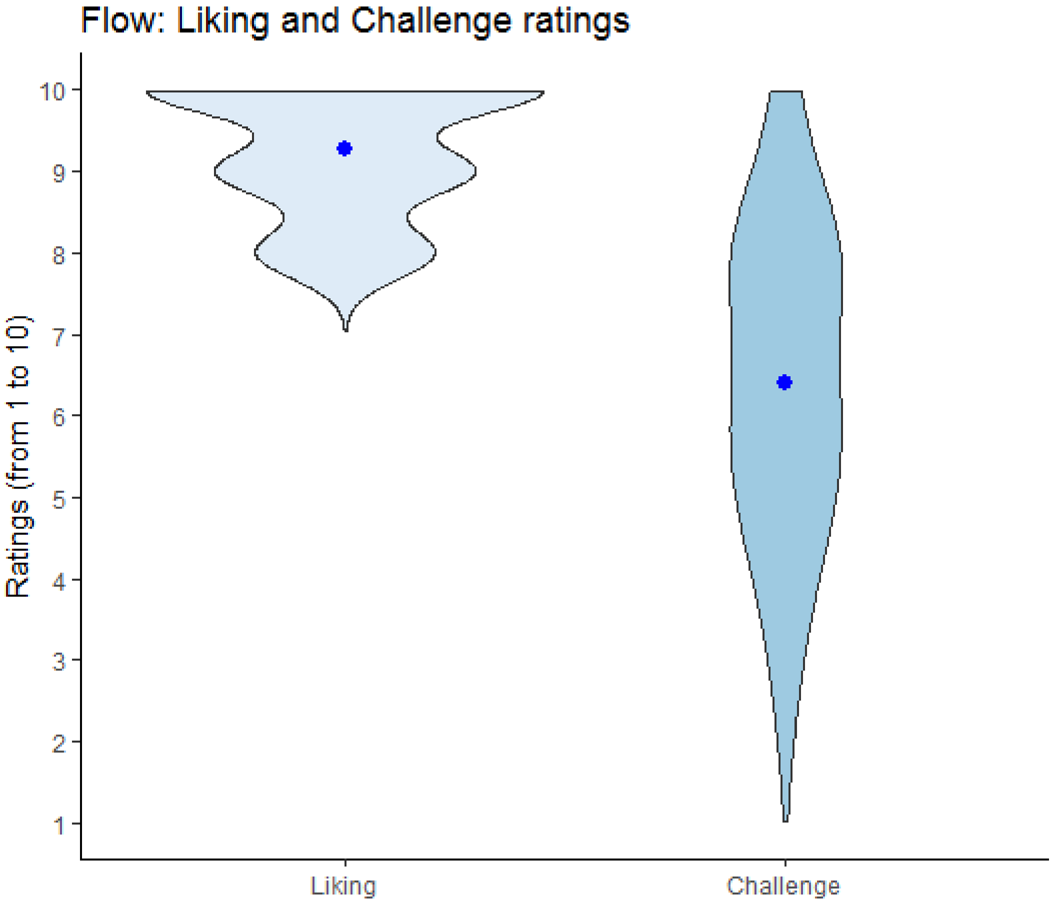

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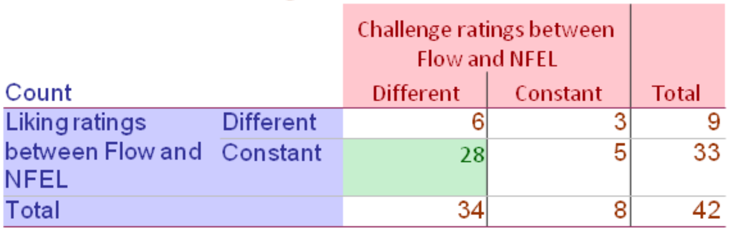
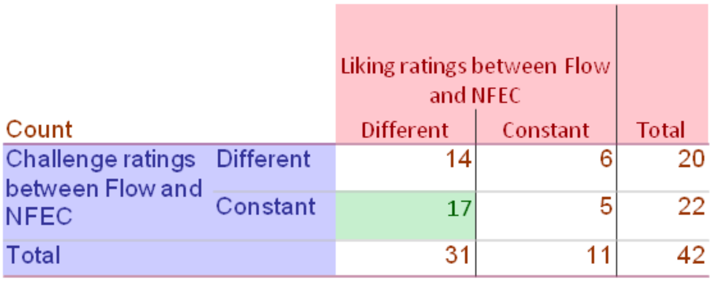
Flow and Non-Flow Equal Liking (NFEL): Challenge and Liking Ratings Crosstabulation



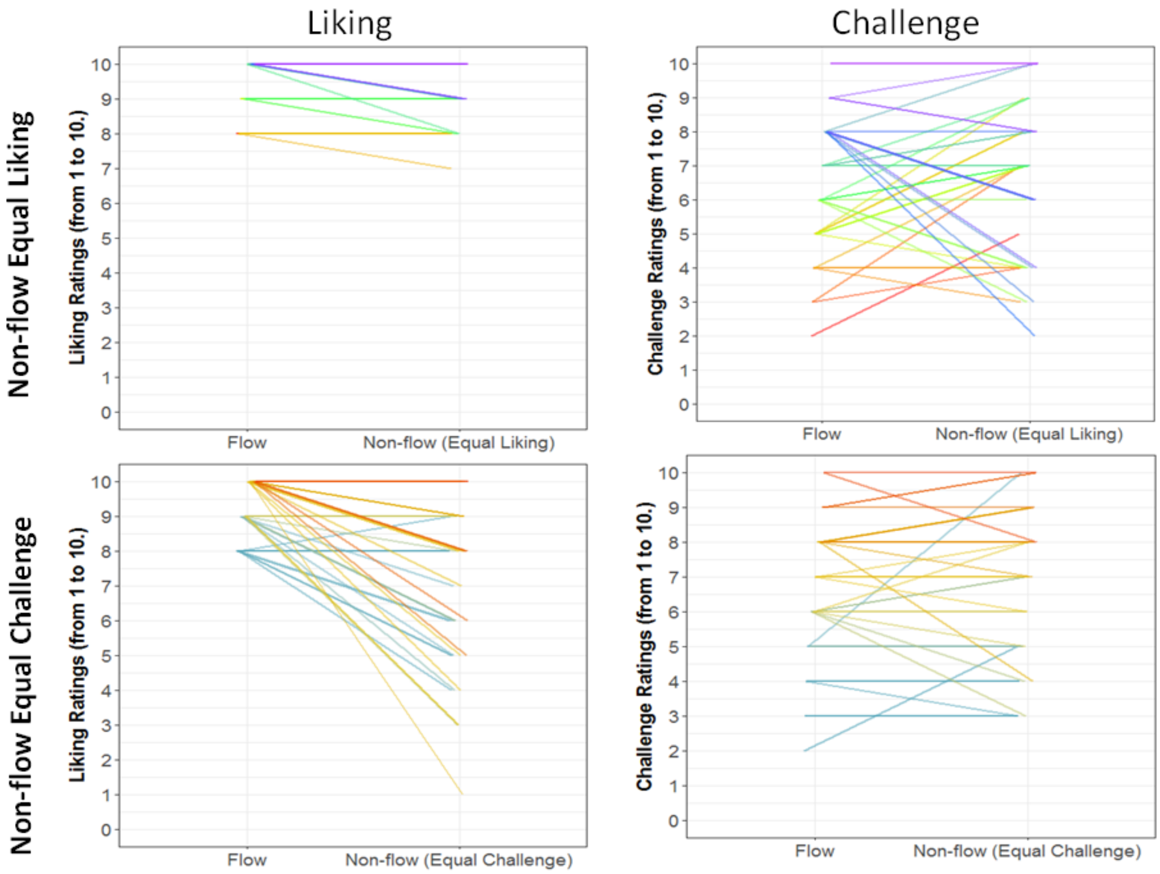
Count		Challenge ratings between Flow and NFEL: Different	Constant	Total
Liking ratings between Flow and NFEL	Different	6	3	9
	Constant	28	5	33
Total		34	8	42

Flow and Non-Flow Equal Challenge (NFEC) : Challenge and Liking Ratings Crosstabulation



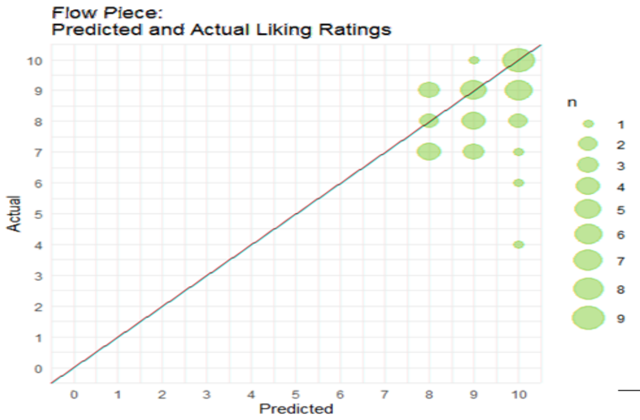
Count		Liking ratings between Flow and NFEC: Different	Constant	Total
Challenge ratings between Flow and NFEC	Different	14	6	20
	Constant	17	5	22
Total		31	11	42

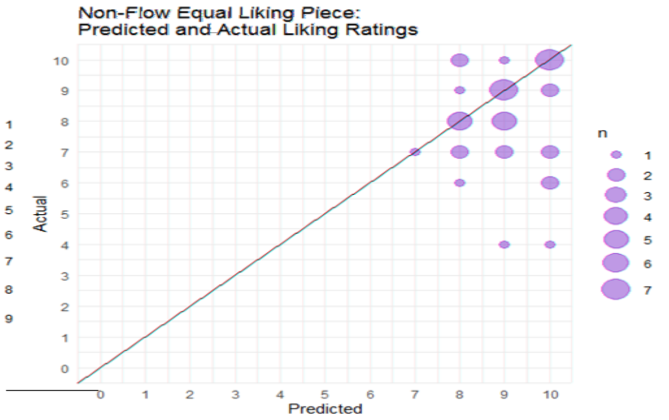
Success of Manipulation: Liking and challenge ratings for selected pieces by condition

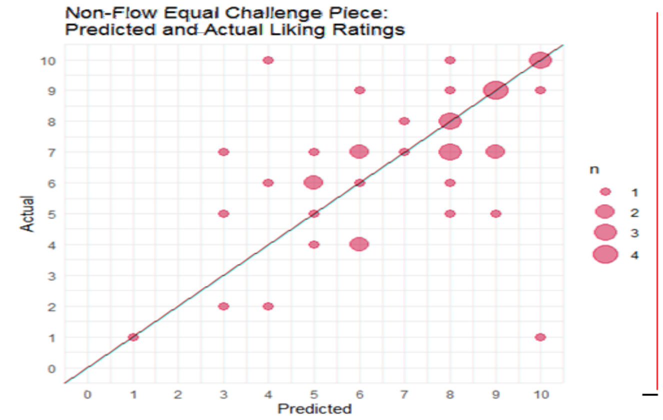


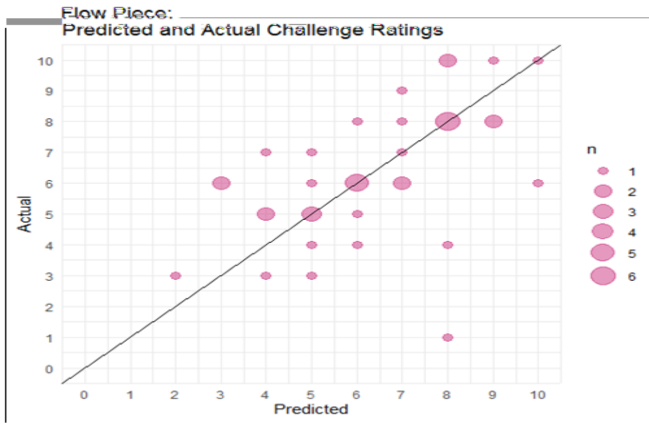
ck n pnl n ij l l ijck ck l p ck ckck ijn l n ckck l nl ijn

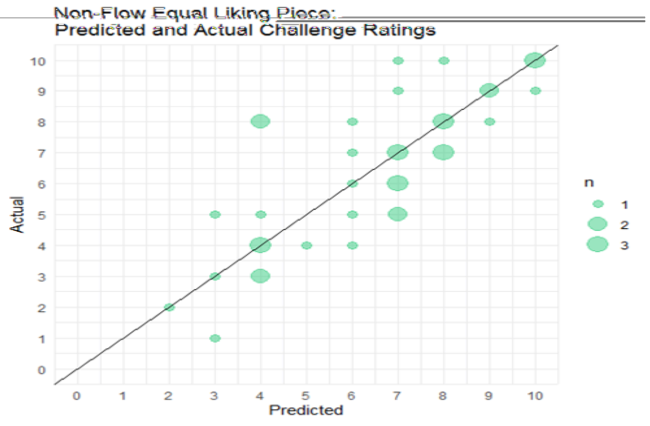
nl nl p

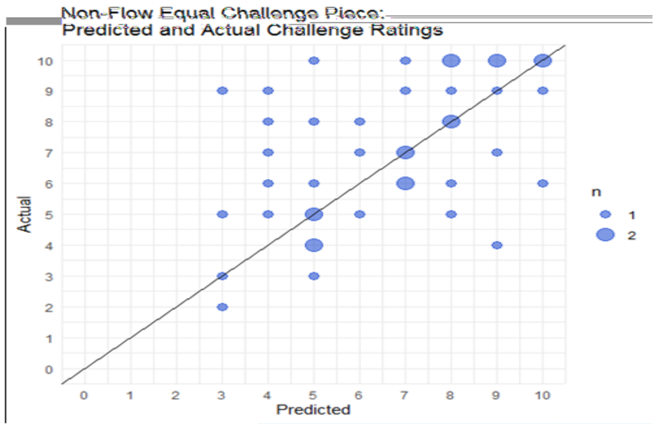












Count	Challenge (compared to			
	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	2	2	2	6
[redacted]	4	10	2	16
[redacted]	10	4	8	22
[redacted]	16	16	12	44

Count	Challenge (compared to			
	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	3	3	0	6
[redacted]	5	6	9	20
[redacted]	3	8	7	18
[redacted]	11	17	16	44

Count	Challenge (compared to usual)			
	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	8	3	4	15
[redacted]	8	3	3	14
[redacted]	5	4	6	15
[redacted]	21	10	13	44

ćk P ćk ŭŋ p n n ćk ćk ŭŋćk ćk l ŭ l l p n ćkćp n ćk n ŭŋćk ćk l ŭ l l p l ćkŭ Bn p nl ćkŭl ćk ćkŭćk ŭ l p ćk ćk ćk nl ćp Bn p n ćk ćkŭl ćk ćkŭćk ćk ćk ćk ćkćk p ćk ćk ćk ćk p n ćkŭ ćk nl ćk v l ćkŭ n n ćk ŭ Bn p l ćk ćkŭl ćk ćkŭćk ćkćp ćkćkŭćpp ŭ ćk nl ćk v n ćkćk nl p ćkćk n ćkćk pv nl ćk v

nl nl	**l**	***r*** **ćk ćk** **ij**	***p***

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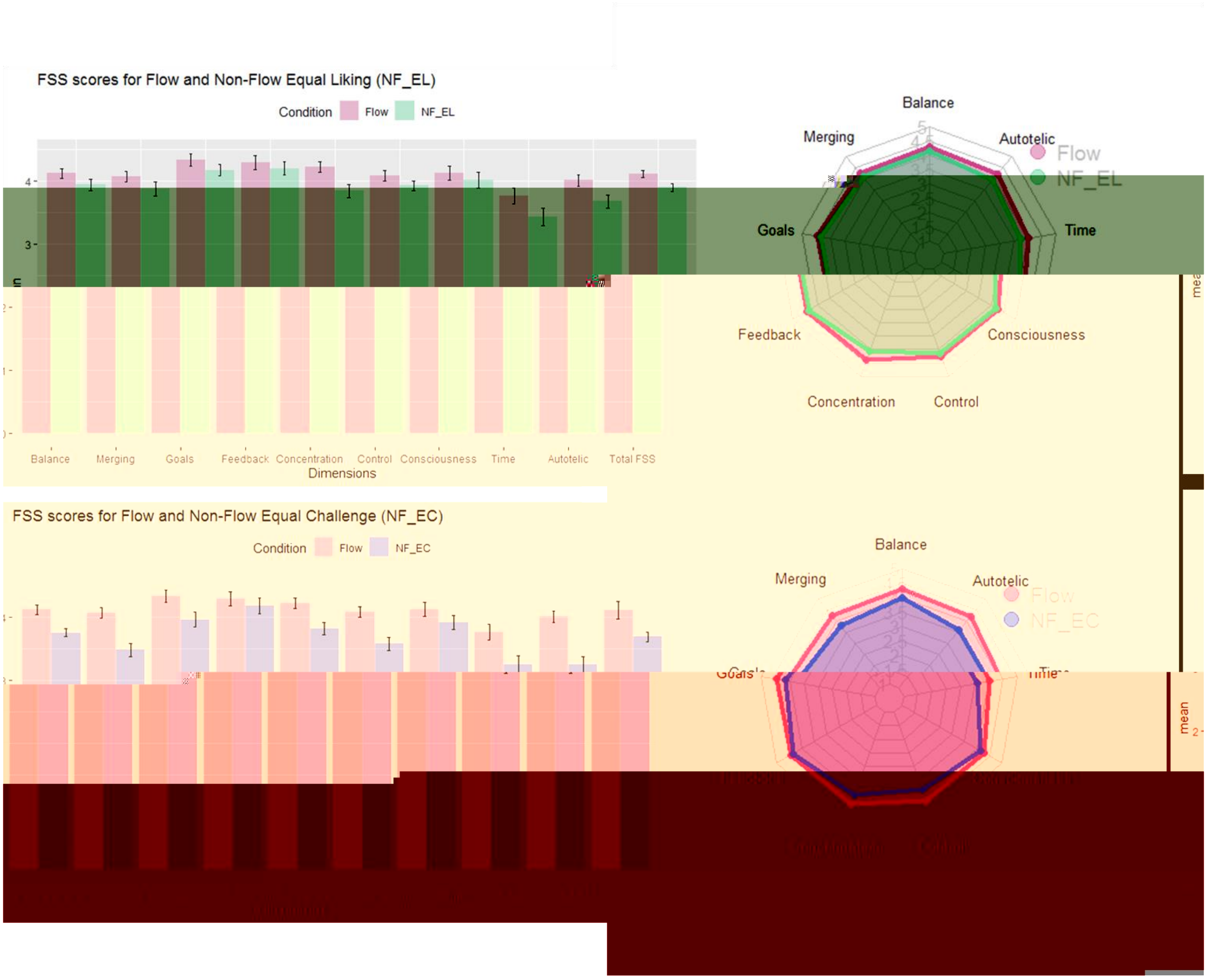
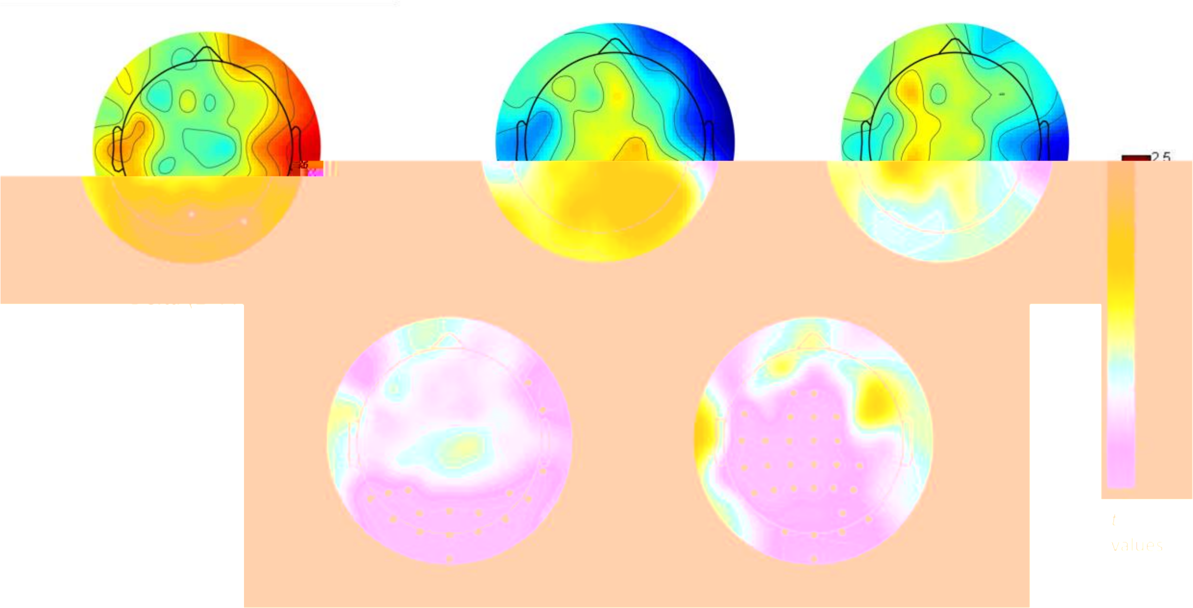


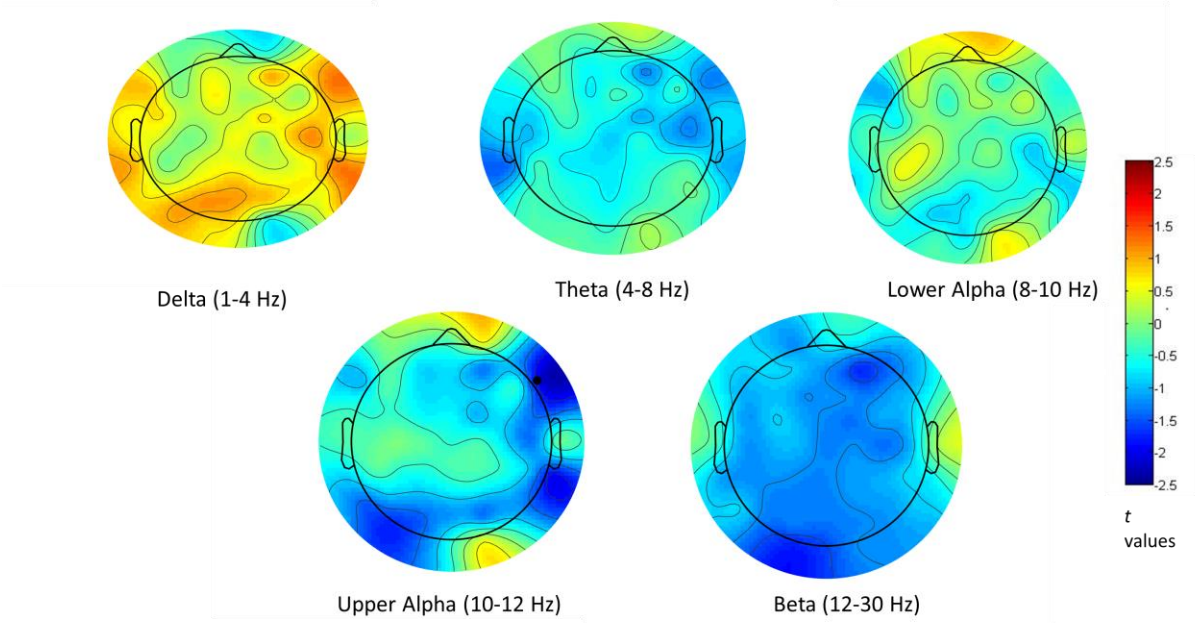
ck ijn p l pn PP p n clp n ijn l ck n l nl ijn nl nl p



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

ck n n ijn p n l ijn l l nl ijn ck ijjy ij ck nl nl p ckj ckp ck ij

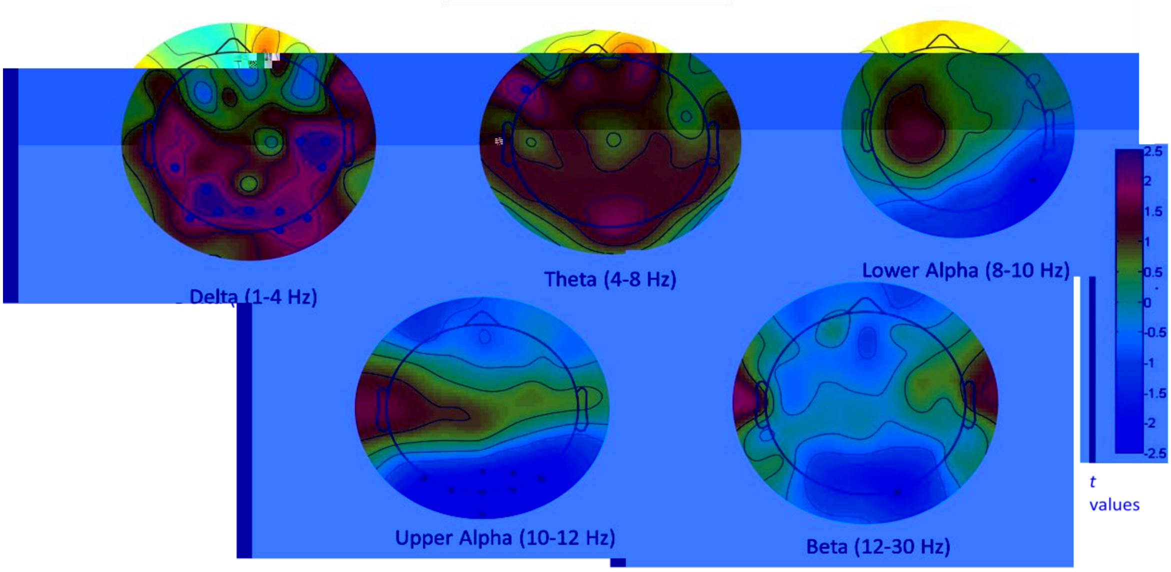
n ck l ck ck ij l ck l p p ck l ckl nl ijn nl nl



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

ćk n n ŭŋ p n l ŭŋ l l nl ŭŋ ćk ŭŭy ŭŭćk l nl nl p ćkŭ ćk

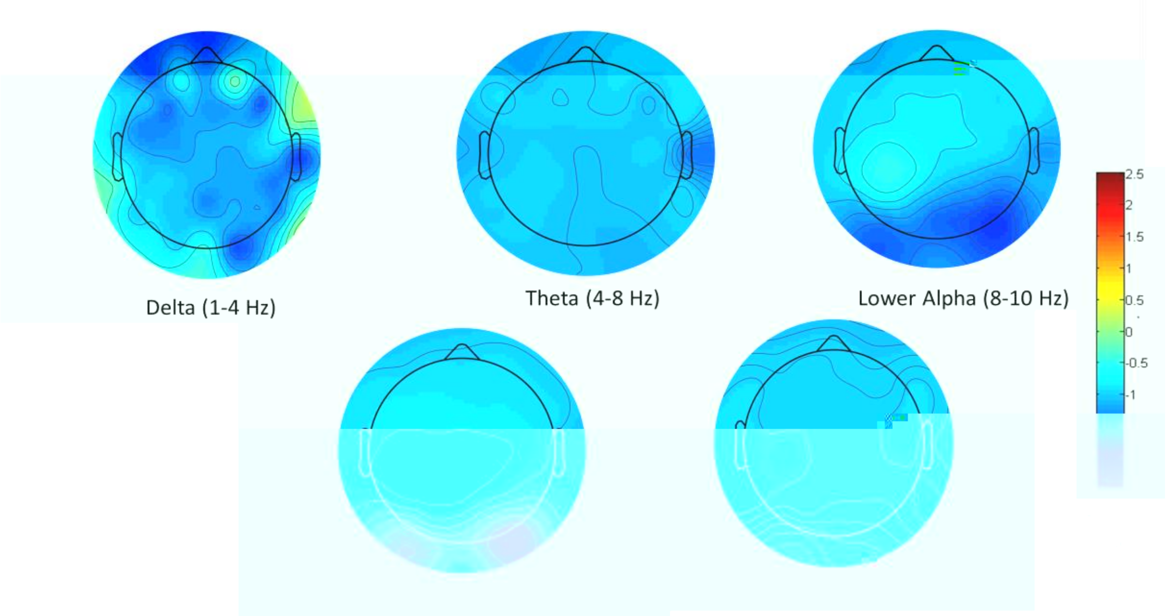
p ćk ŭ n ćk l n ćk ćk ćkćk ŭŋ l l nl ŭŋ nl nl p



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

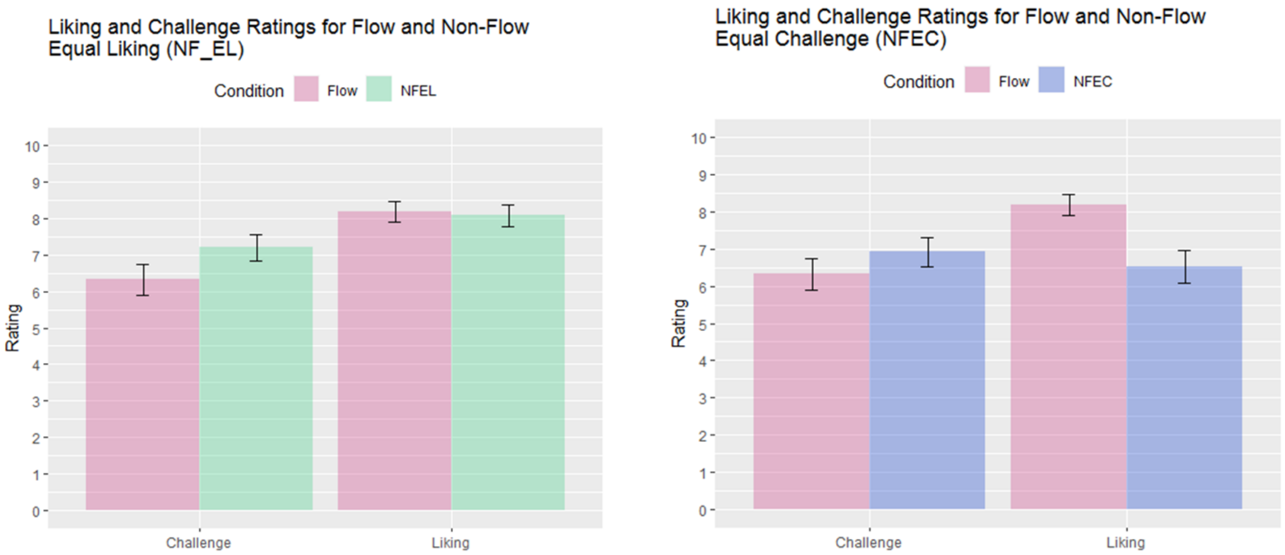
ďk n n ŋŋ p n l ŋŋ l l nl ŋŋ ďk ŋŋy ŋ ďk nl nl p l pnŋ ďk

p ďk ŋ n ďk



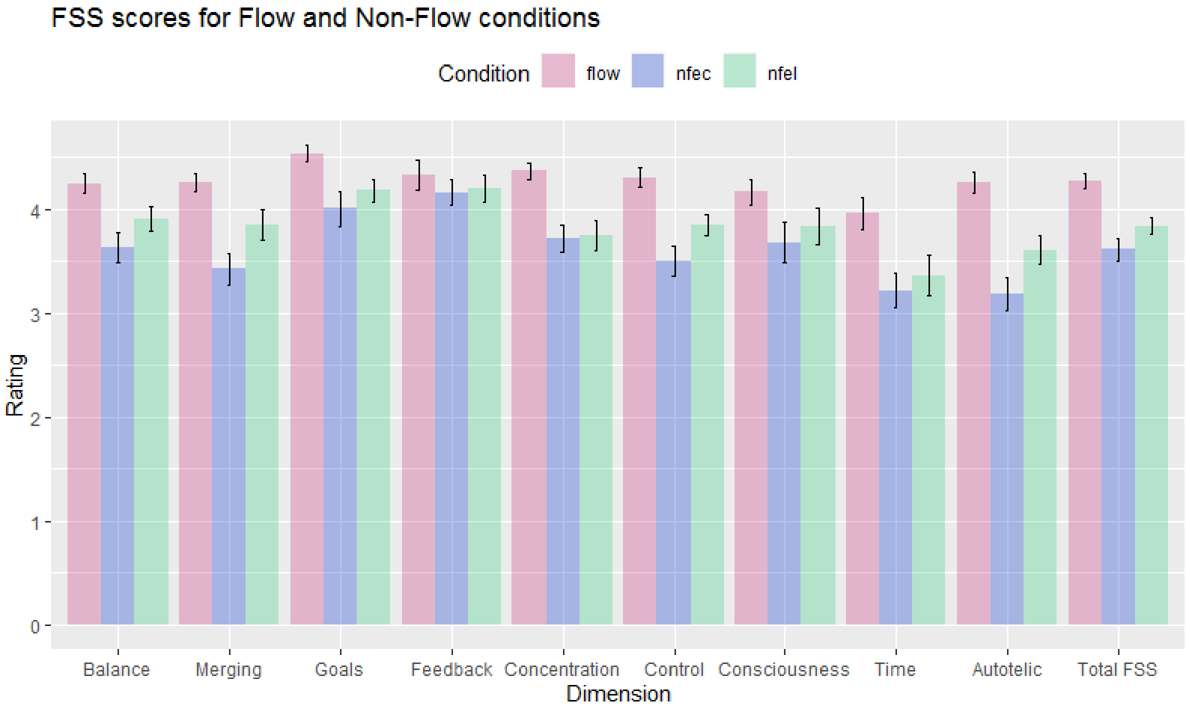
ďk n n ŋŋ p n l ŋŋ l l nl ŋŋ ďk ŋ ŋŋďk ďk nl nl p l pnŋ ďk
p ďk ŋ n ďk

3. 3. 3. EEG findings part 2



[illegible]

[illegible]

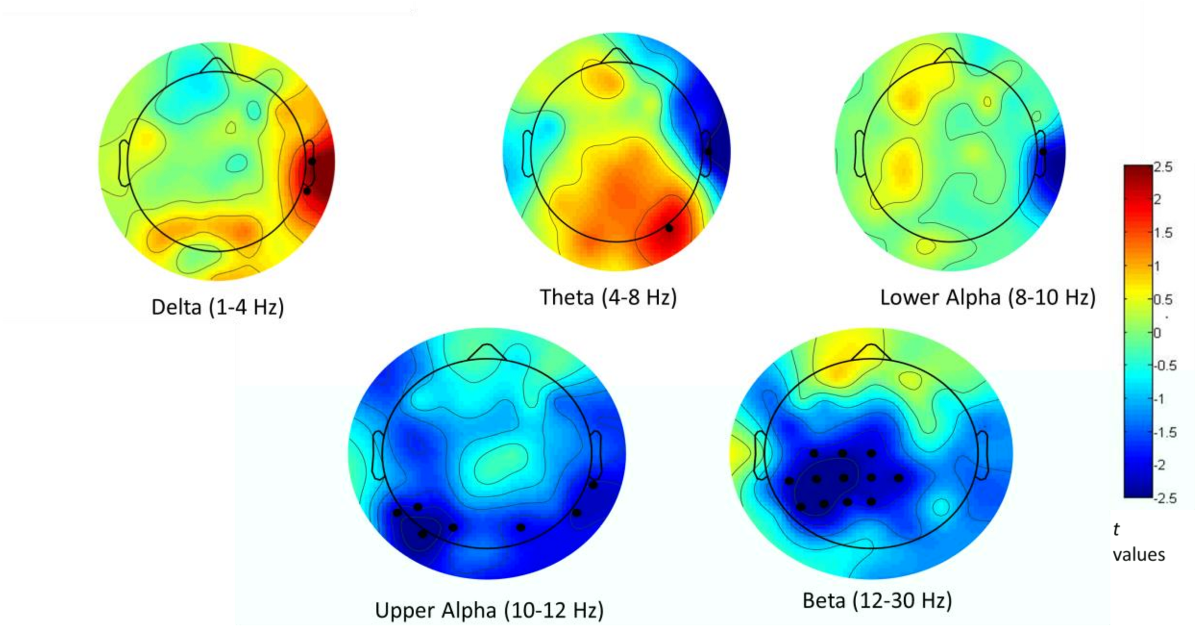


ck PP p n cl̥p n ckp pck n l p p n ck clp ijn p n clp l ck ijn

nl nl l

**. The mean difference is significant at the 0.01 level (2-tailed).

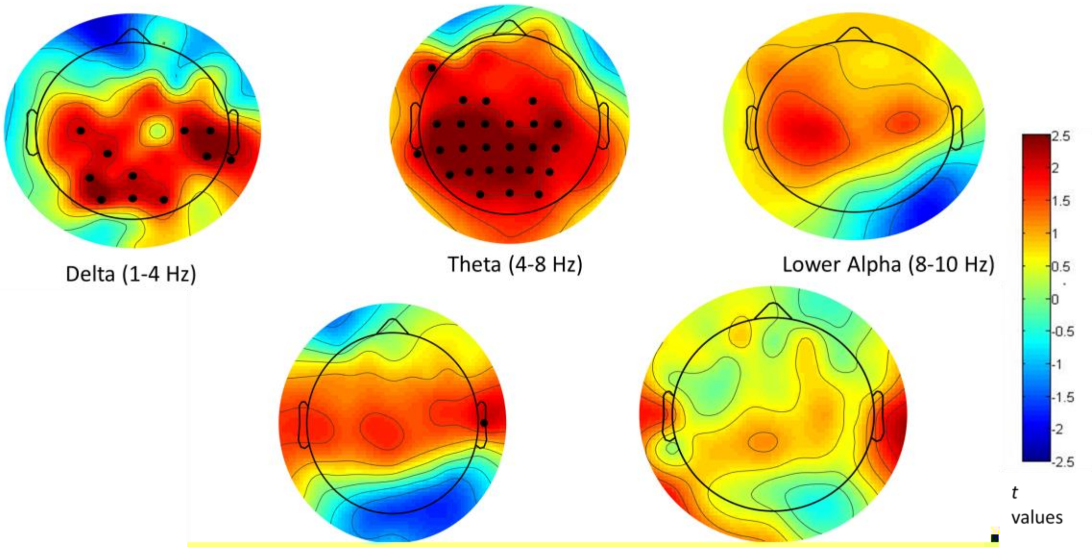
ŋĉk P v n LM nl PPpn ĉp n ŋ l ĉkpnlp



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

ĉk n n ŋn p n l ĉkŋ ĉkp ĉk ŋ n ĉk ĉk ĉkĉk ŋn l l nl ŋn ĉk ŋŋ l

nl nl p



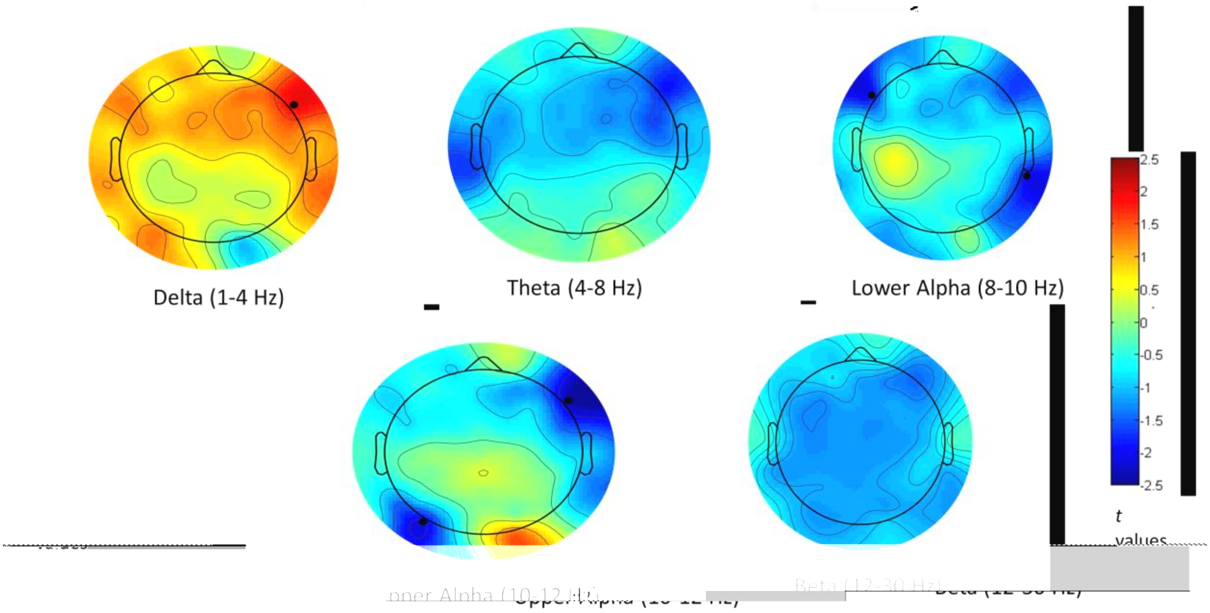
Upper Alpha (10-12 Hz)

Beta (12-30 Hz)

Topoplots of *t*-values by comparing EEG power of five frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

ck n n ÿjn pp n l ckck ckp l pnÿj ckp ck ÿj n ck ck ckkk ÿjn l ck ÿj

ÿj l nl nl p



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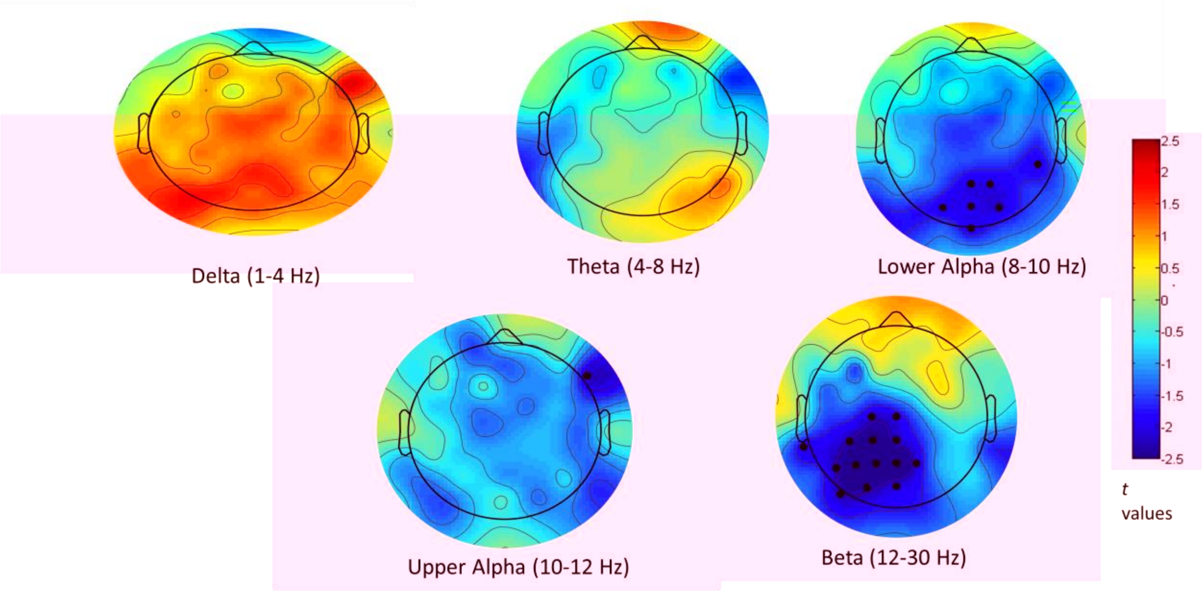
Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow ar flow states. Red indicates that power is higher in the flow condition while blue indicates power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are inc black dots.

ck n n ij pp n l ckck clp l ckj ckp ck ij n ck ck ckck ijn l l nl ijn

ck ij ijjck ck nl nl p

3. 3. 4. EEG findings: High flow vs Low flow



Delta (1-4 Hz)

Theta (4-8 Hz)

Lower Alpha (8-10 Hz)

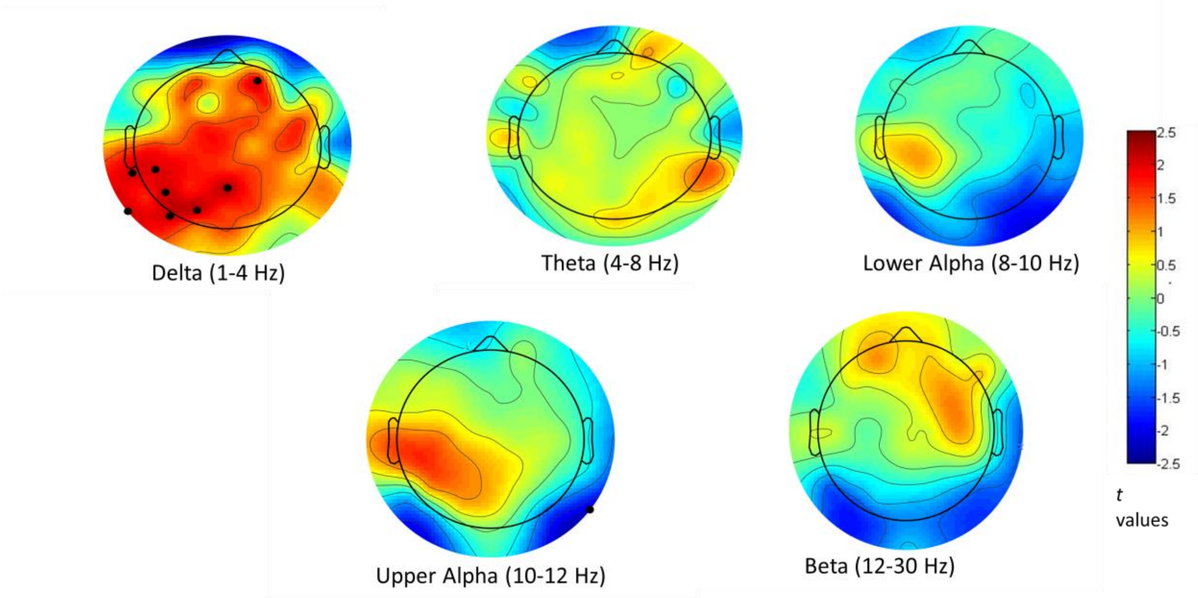
Upper Alpha (10-12 Hz)

Beta (12-30 Hz)

Topoplots of *t*-values by comparing EEG power of seven frequency bands between high flow and low flow states. Red indicates that power is higher in the high flow condition while blue indicates that the power is higher in low flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

ćk n n ŋn p n l ćkj ćk n ćk l ćkpćkp nl ćk ćkp ŋn p n ćk l ćk

pćkp nl ćkŋn ćkp ŋn p n ćk



Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the high flow condition while blue indicates that the power is higher in low flow condition. Statistically significant electrodes (p < .05) are indicated by black dots.

ćk n n ijn p n l pnij ćkp ćk ij n ćk l ćkpćkpp nl ćk ćlp ijn

p n ćk l ćkpćkpp nl ćkijn ćlp ijn p n ćk

3. 4. Discussion

3. 4. 1. Behavioural data

3. 4. 2. Neural data

3. 4. 3. Limitations

3. 4. 4. Conclusion

Chapter 4 Interoception in musicians' flow experience

4. 1. Introduction

4. 1. 1. Interoception

4. 1. 2. Interoception in flow

4. 2. Methods

4. 2. 1. Statistical analyses

4. 2. 2. EEG recording and analysis

4. 2. 3. Preprocessing

4. 2. 4. ERP analysis

4. 2. 5. EEG Statistical analysis

4. 3. Results

4. 3. 1. Behavioural results

P v n ijn p n cljo

	Minimum	Maximum	Mean	Std. Deviation
	3.08	4.69	3.8428	0.36392
	2.94	4.97	4.1016	0.44497
	3.11	4.97	4.1231	0.47619
	2.69	4.78	3.8592	0.41881
	2.72	4.78	3.9312	0.44992
	2.47	4.53	3.6900	0.46384
	2.39	4.44	3.6862	0.53795

ijck Bcljo cljo p p n ijn p n cljo

ijck

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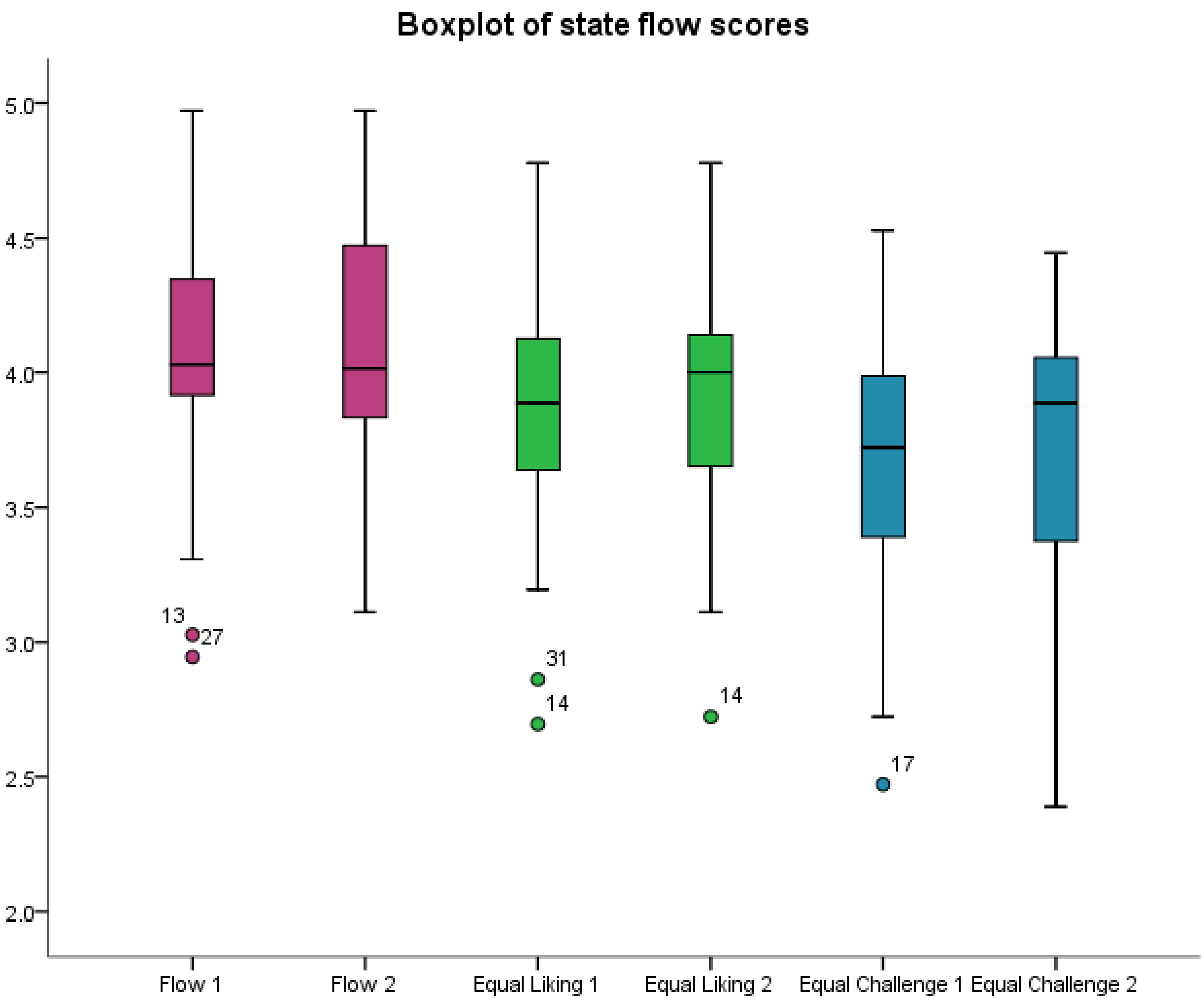
pćk n pnl pn ćk ćk ijn p n ćlp ćlv PB

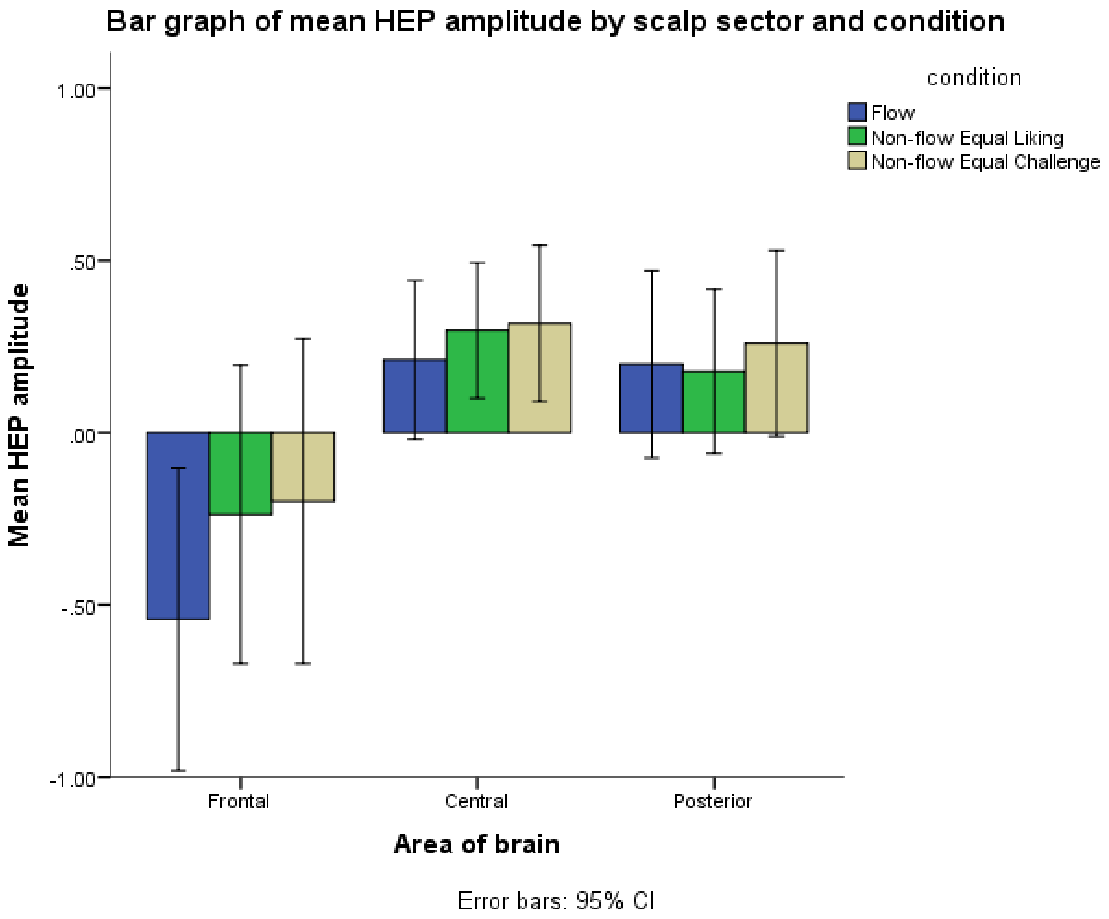
ijćk pćk n pnl p n ijn p n ćlp npp nl nl p



ck n ĳn n p np nl ĳ l p ck ĳn p n cp B P B p np nl ĳ ĳn p n ck ĳn

L Lnl ĳn ck ĳĳ l L Lnl ĳn ck ĳ ĳĳck ck

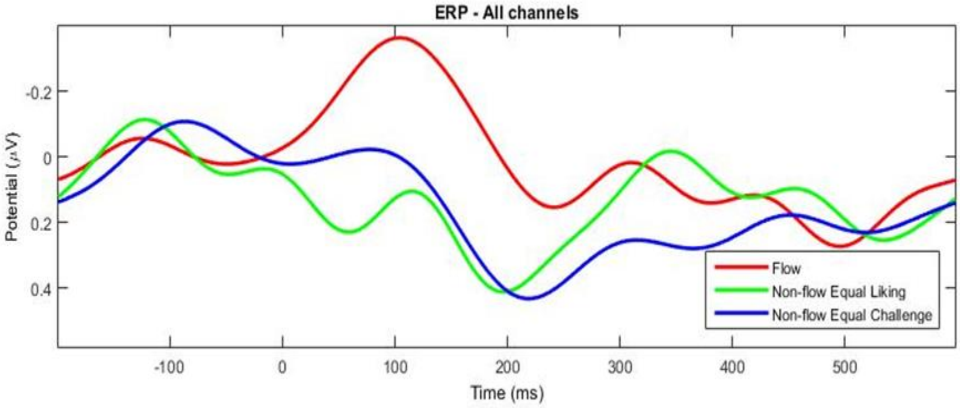
4. 3. 2. ERP results



ck n ckl ij ck ck ckk p n p n ck v p ij pck n ck

p l l l ck nl ck ckk p ij pck n l nl nl pckk p n ck ck v ckij ck

l ck ck ij ckl ck nl ij ck nl p ij ijy l ck ijn nl nl



[illegible]

4. 4. Discussion

4. 4. 1. Behavioural results

4. 4. 2. ERP results

4. 4. 3. Limitations

4. 4. 4. Conclusion

Chapter 5 Challenge-skill balance in climbers

5. 1. Introduction

5. 2. Methods and materials

5. 2. 1. Design

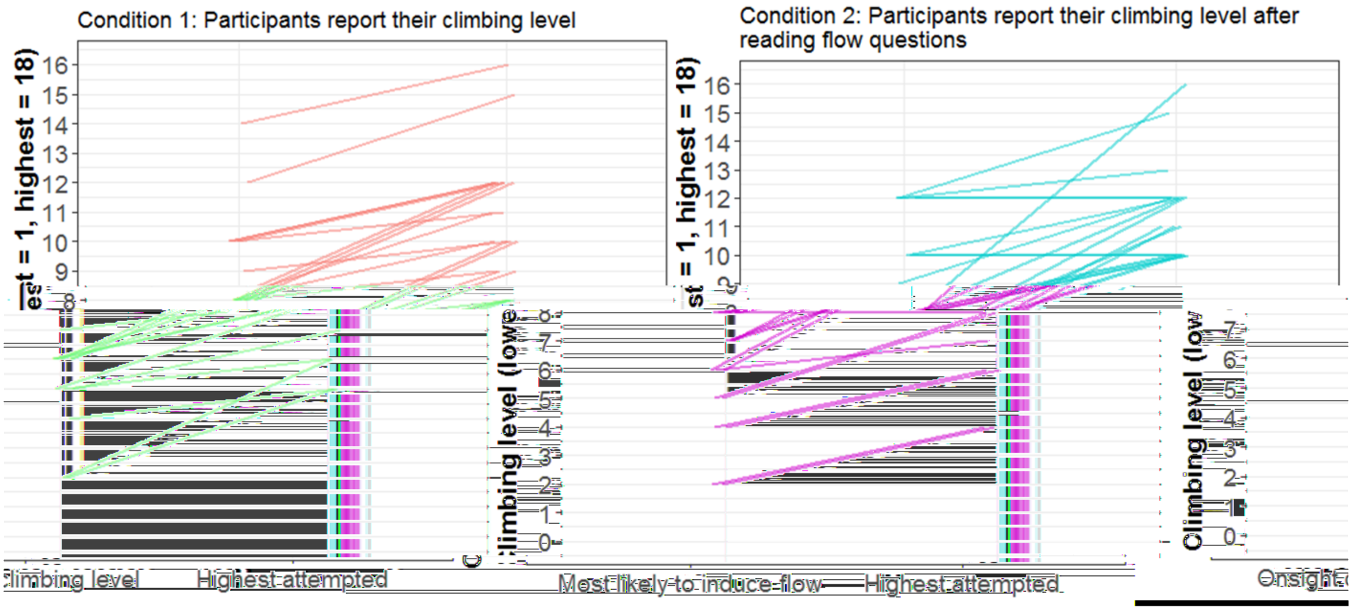
5. 2. 2. Participants

5. 2. 3. Materials

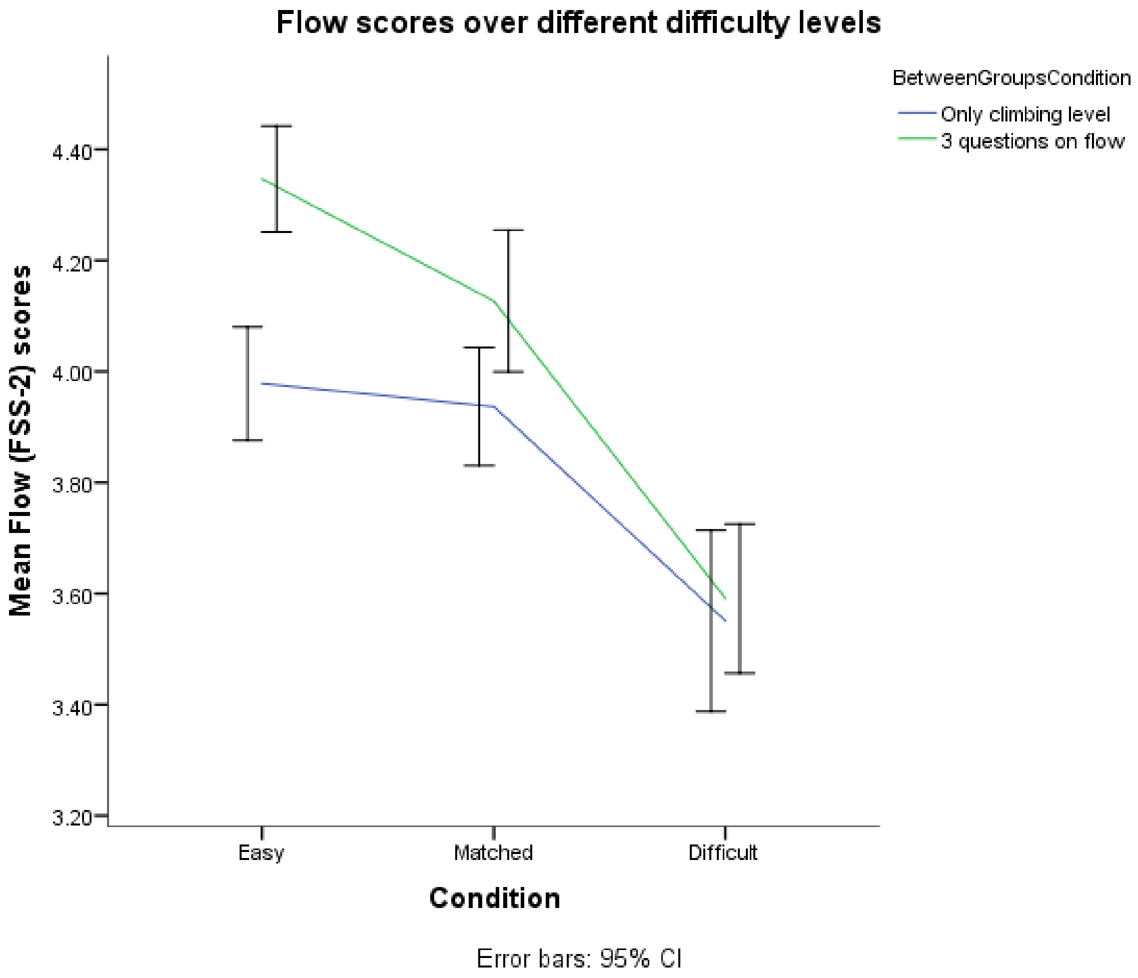
5. 2. 4. Procedure

5. 2. 5. Analysis

5. 3. Results


Condition 1: Participants report their climbing level
Condition 2: Participants report their climbing level after reading flow questions
est = 1, highest = 18)
st = 1, highest = 18)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Climbing level (lowe
Climbing level (low
Climbing level
Highest attempted
Most likely to induce flow
Highest attempted
Onsight

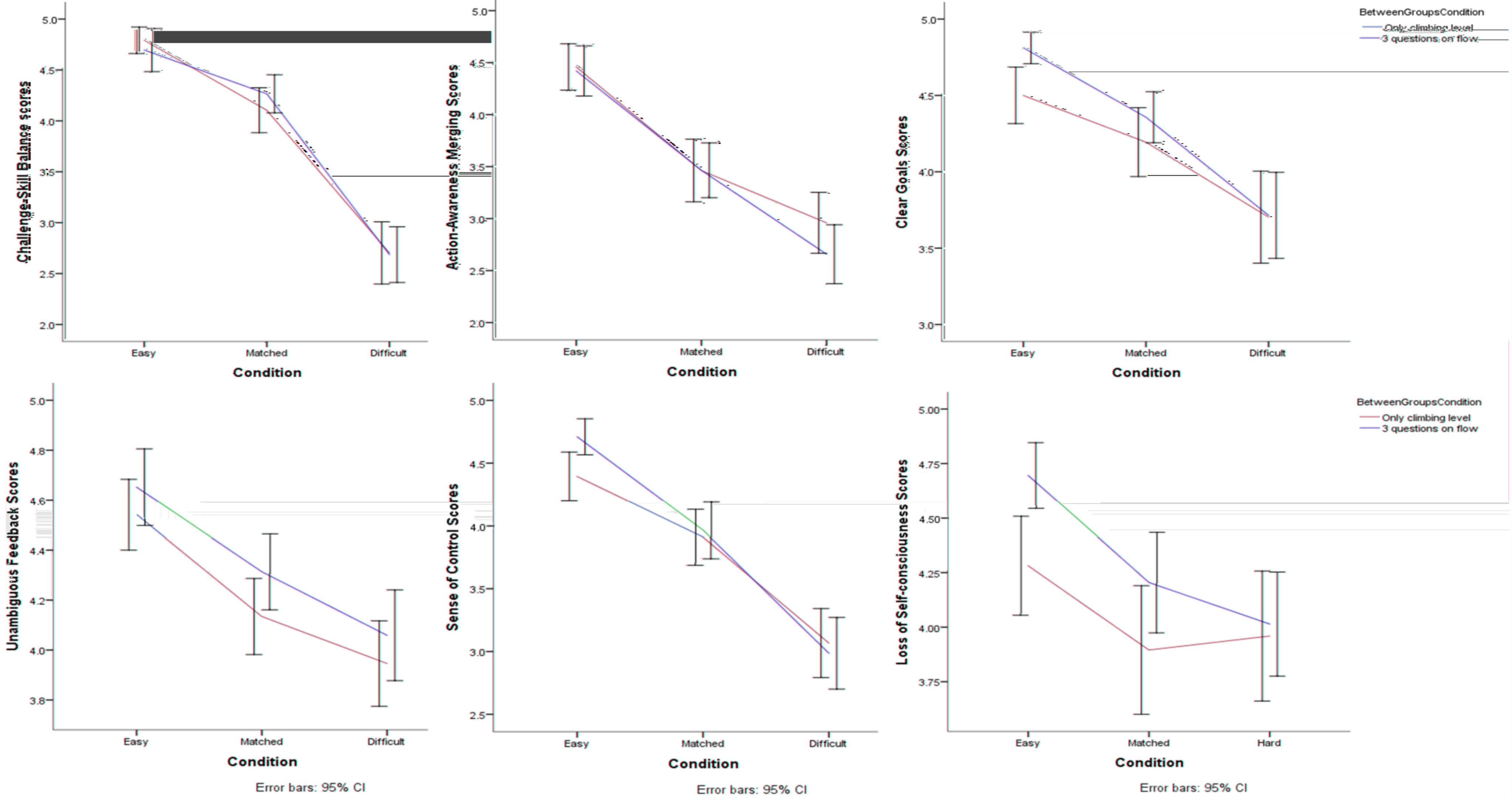
[illegible]



ck ij ckp ij ck n clp ckck ijv ijck ckijp n l ck nl nl pn n ck n

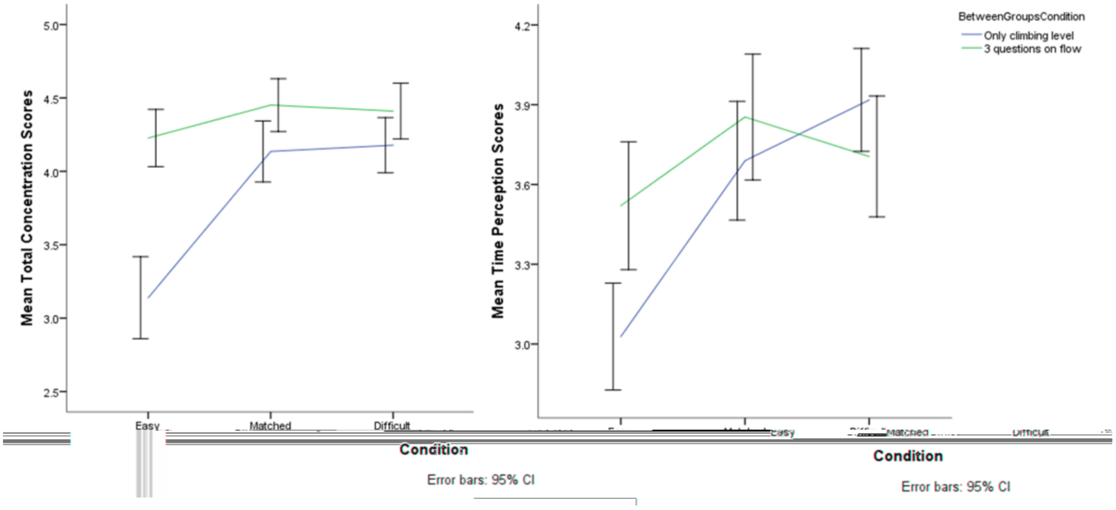
ijn l p nl P pl ijy ijn p n clp ckckl n ck clp ck ck nl nl

Scores on the flow dimensions of challenge-skill balance, action-awareness merging, clear goals, unambiguous feedback, sense of control and loss of self-consciousness show a linear decrease over difficulty levels.



ck ij p n ckp n ij ckpnl p P n ck ij ckpnl p ijck ckp ij ij l ck nl ck ckp ck l ijck n ijp l n p ckck pckpckn
nl nij l ijppn pckj nl p n pl ckp ck ckpck p ijck ckl ckpckp

Total concentration and Time Perception show a trend towards an inverted u-shaped curve



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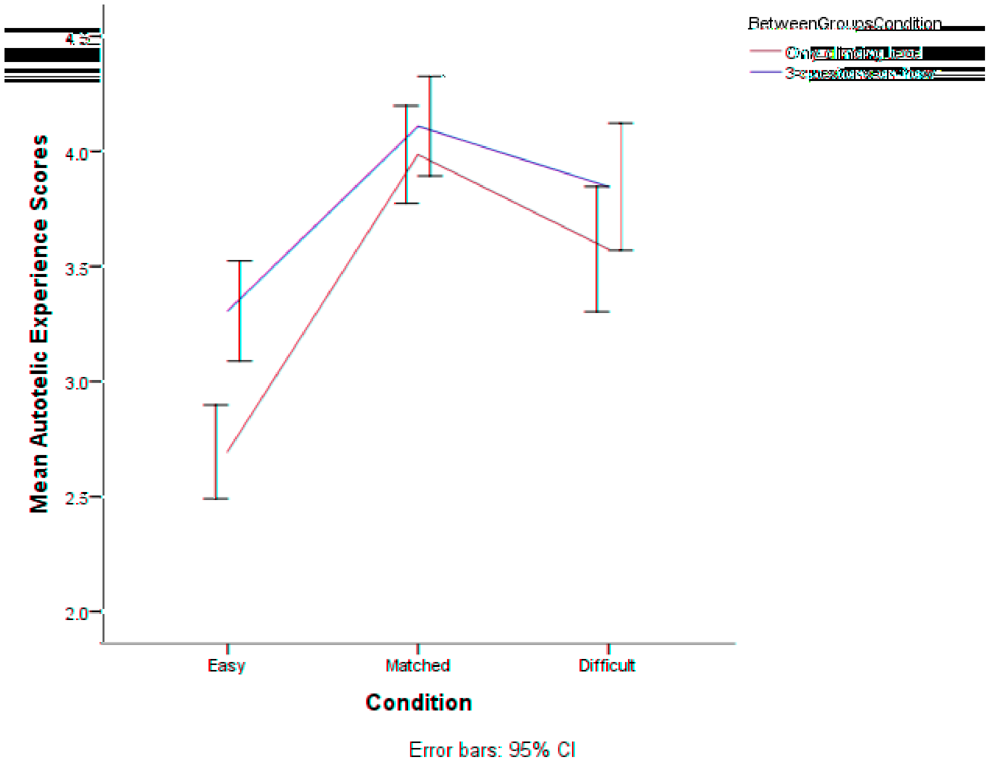
BetweenGroupsCondition
Mean Autotelic Experience Scores
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Difficult
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Error bars: 95% CI

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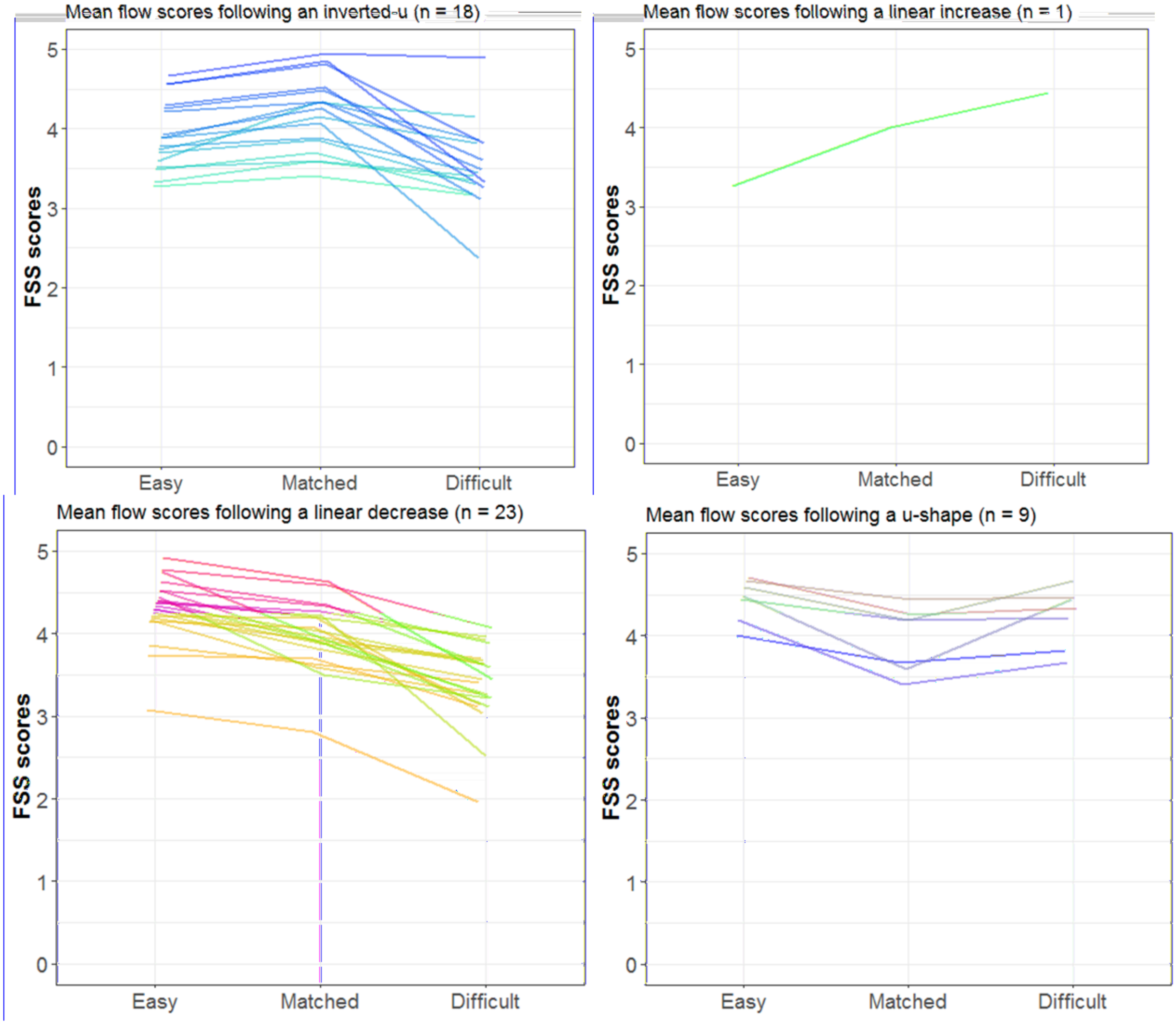

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ij nl nl

5. 4. Discussion

5. 4. 1. Effect of a flow induction outside the lab

5. 4. 2. Effect of the between-subject manipulation

5. 4. 3. Limitations of the experiment

5. 4. 4. Implications for studying the neural correlates of flow outside the lab

5. 4. 5. Conclusion

Chapter 6 Investigating Links between Grit, Growth Mindset and Flow in Musicians

6. 1. Introduction

6. 2. Methods

6. 2. 1. Design

6. 2. 2. Participants

6. 2. 3. Materials

6. 2. 4. Procedure

6. 2. 5. Statistical Analyses

6. 2. 6. Results

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6. 2. 7. Bivariate Correlation Tests

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ÿck n ckj nl p n ÿn p p ÿckp p ÿ l l nl p ck n pl ckp ck n nl ÿp ÿ v l ck n l ck l ckv

6. 2. 8. Hierarchical Linear Regression

6. 3. Discussion

Chapter 7 Dispositional flow in resting state data: an exploration of frontal asymmetry, emotional intelligence and flow

7. 1. Emotional Intelligence and Dispositional Flow Across Domains

7. 1. 1. Introduction

7. 1. 2. Methods

7. 1. 2. 1. Design

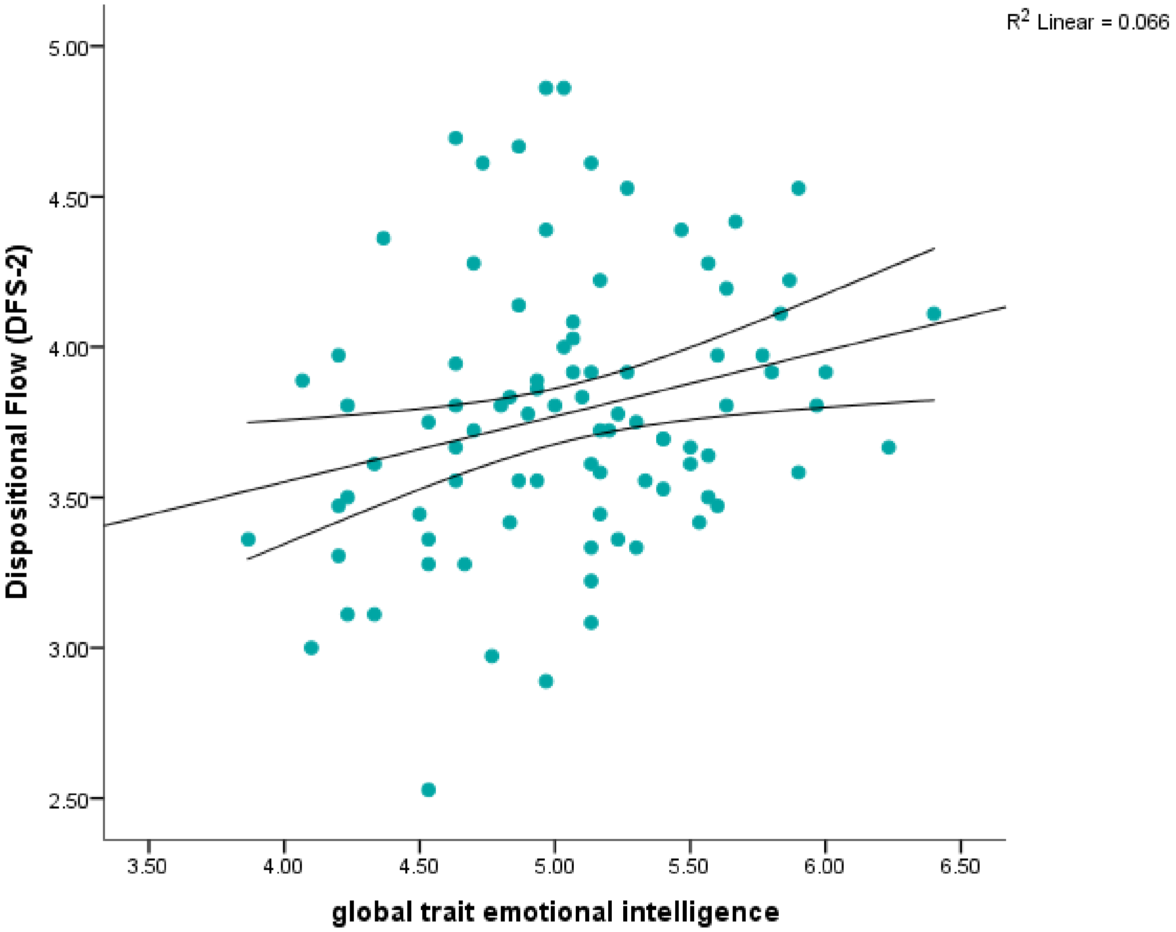
7. 1. 2. 2. Participants and procedure

7. 1. 2. 3. Materials

7. 1. 2. 4. Statistical Analysis

7. 1. 3. Results

7. 1. 3. 1. Emotional Intelligence and Flow in Musicians



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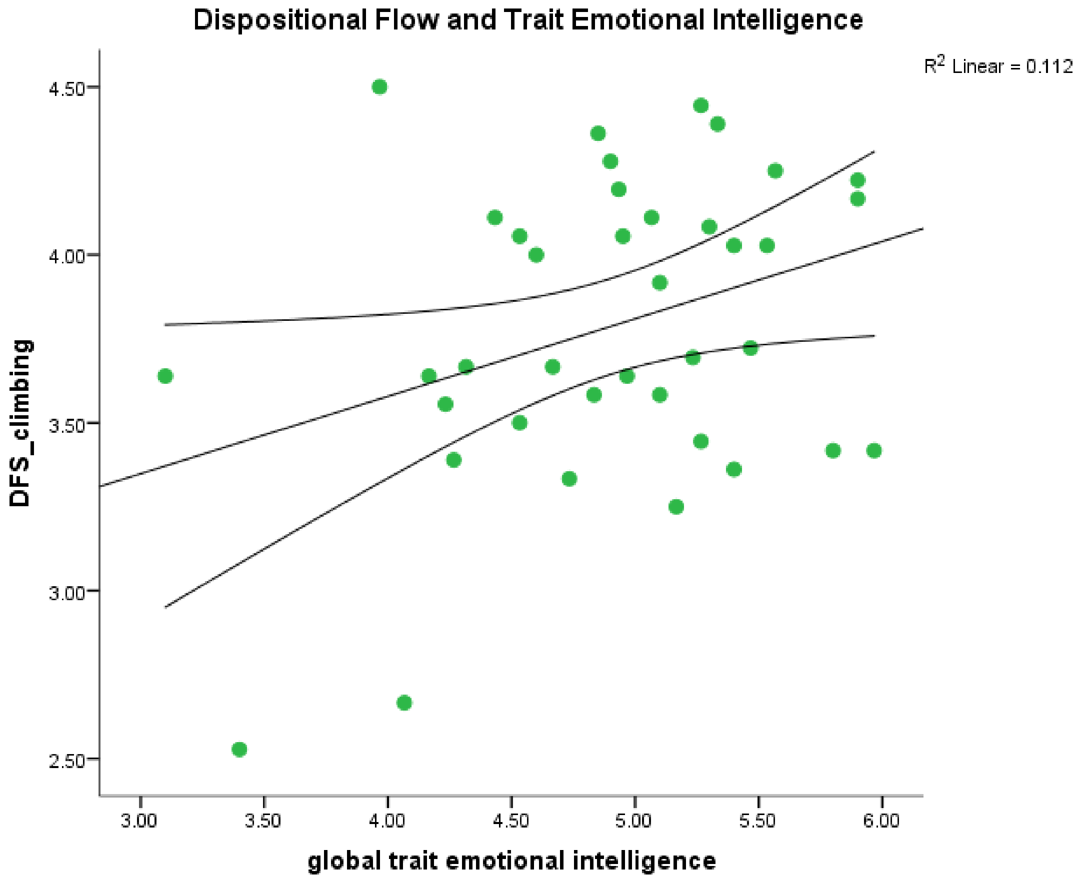
7. 1. 3. 2. Emotional Intelligence and Flow in Climbers



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7. 1. 3. 3. Emotional Intelligence and Flow in Daily Life

Correlations between trait EI, its subscales and flow in general life (n = 36) and in music listening (n = 37)

	well_being	self_control	emotionality	sociability	Flow in general life	Flow in music listening
global trait emotional intelligence	.807**	.708**	.839**	.686**	.575**	0.254
	0.000	0.000	0.000	0.000	0.000	0.129
well being		.557**	.555**	0.309	.503**	0.272
		0.000	0.000	0.063	0.002	0.103
self control			.392*	0.294	.401*	-0.075
			0.016	0.078	0.015	0.658
emotionality				.582**	.423*	0.265
				0.000	0.01	0.113
sociability					.388*	0.308
					0.02	0.064

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

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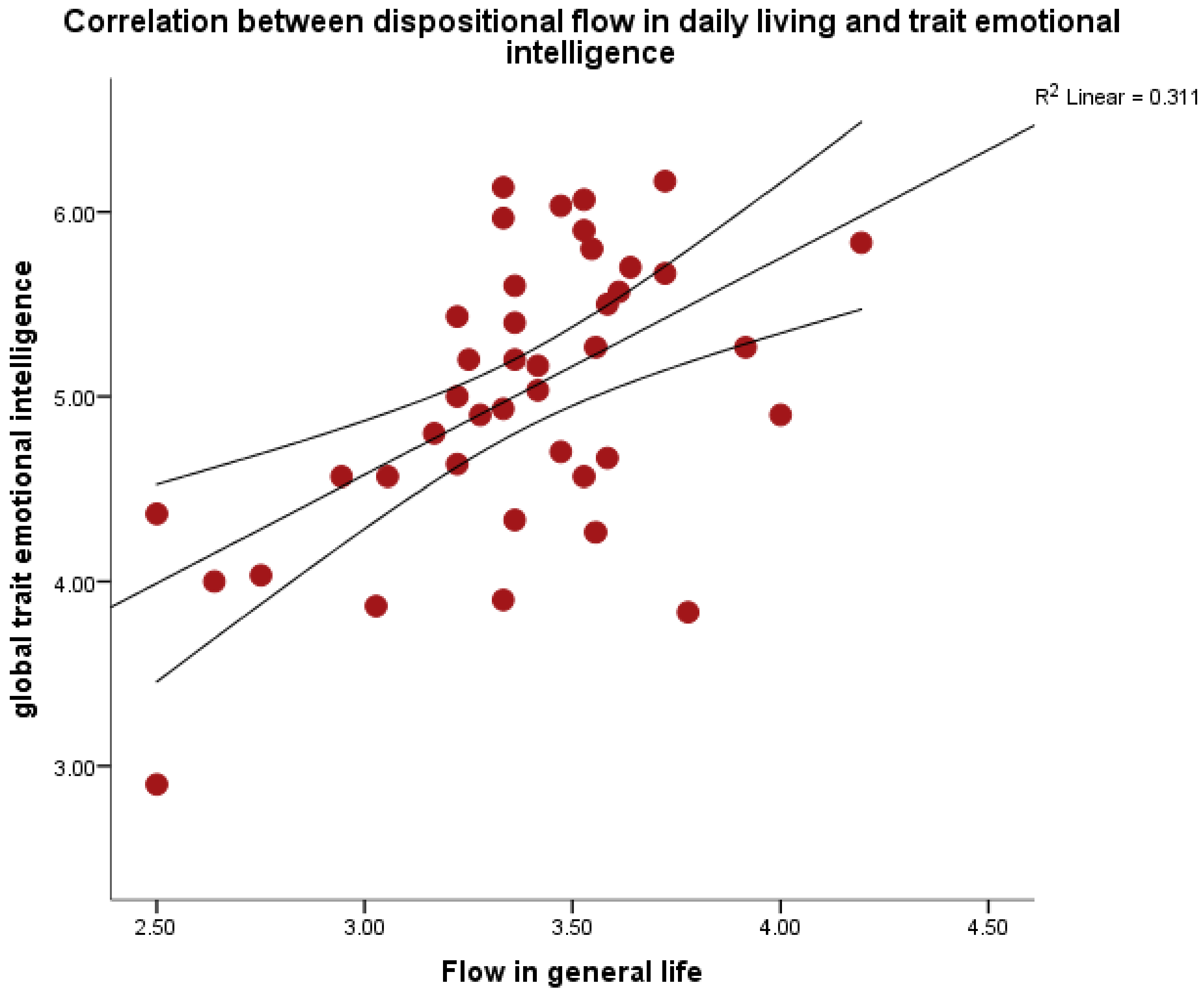

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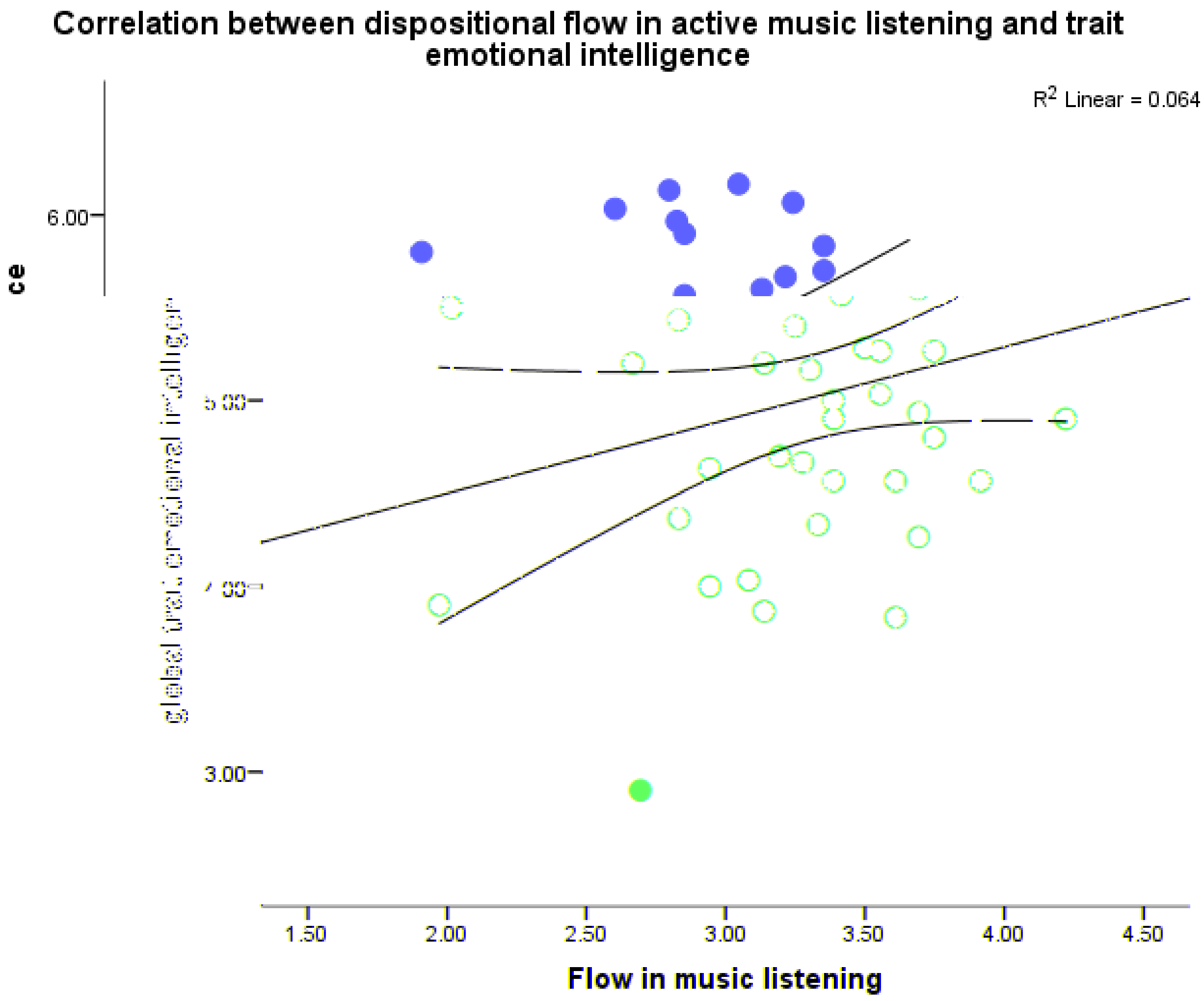

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7. 1. 4. Interim discussion

7. 2. Frontal asymmetry, flow experience and trait EI in musicians

7. 2. 1. Introduction

7. 2. 2. Methods

7. 2. 2. 1. Design

7. 2. 2. 2. Participants

7. 2. 2. 3. Materials

7. 2. 2. 4. Experimental procedure

7. 2. 2. 5. EEG recording and analysis

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7. 2. 2. 6. Preprocessing

7. 2. 2. 7. Time-frequency analysis

7. 2. 2. 8. Frontal asymmetry indices

7. 2. 2. 9. Individual alpha frequency

7. 2. 2. 10. Statistical analysis

7. 2. 3. Results

7. 2. 3. 1. Correlations between frontal alpha asymmetry and global trait intelligence and its subscales

		global trait emotional intelligence	well-being	self-control	emotionality	sociability
Frontal alpha (8-13Hz) asymmetry index	Pearson Correlation	-0.120	-0.012	-0.137	-0.106	-0.041
	Sig. (2-tailed)	0.255	0.910	0.194	0.315	0.699

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

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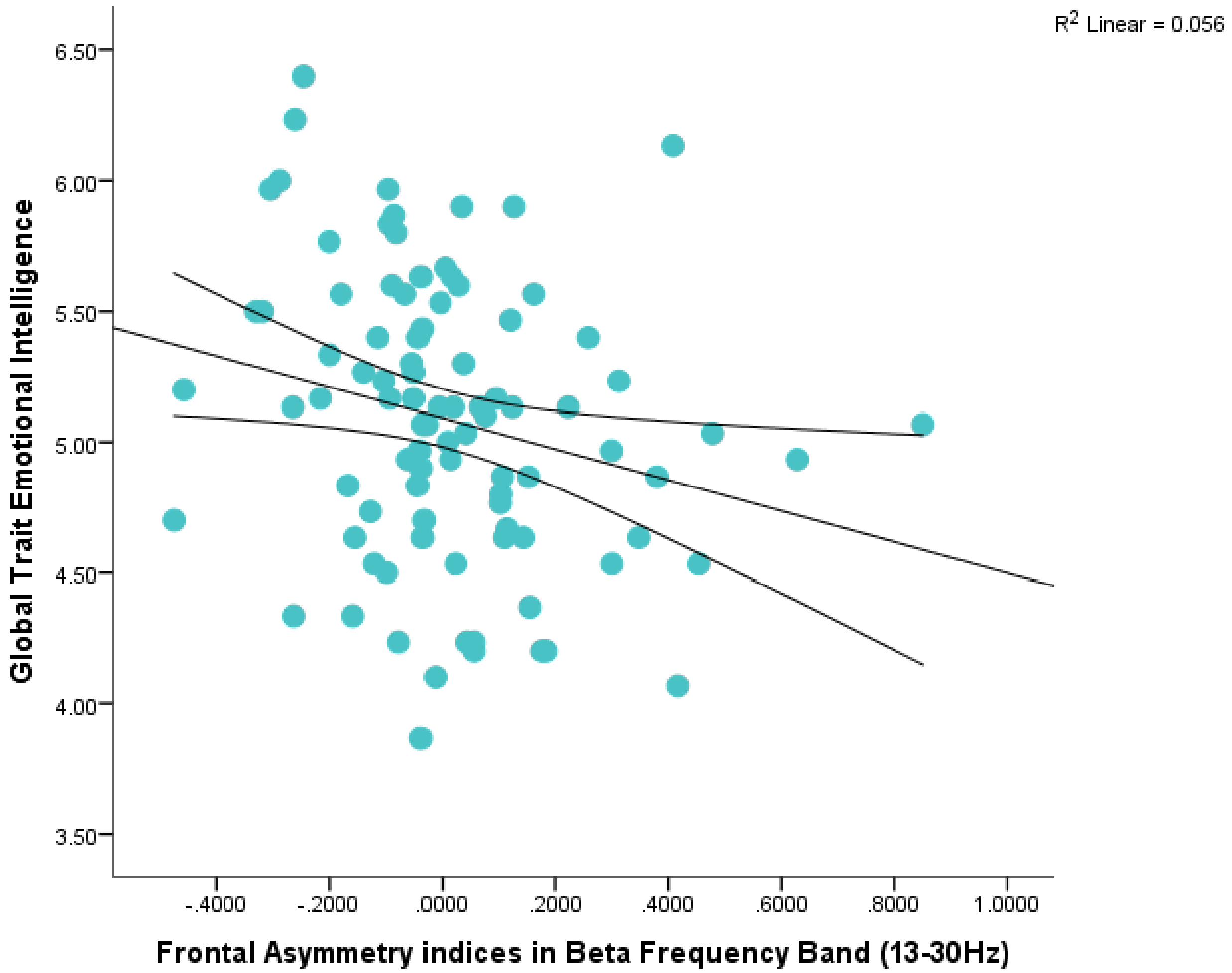

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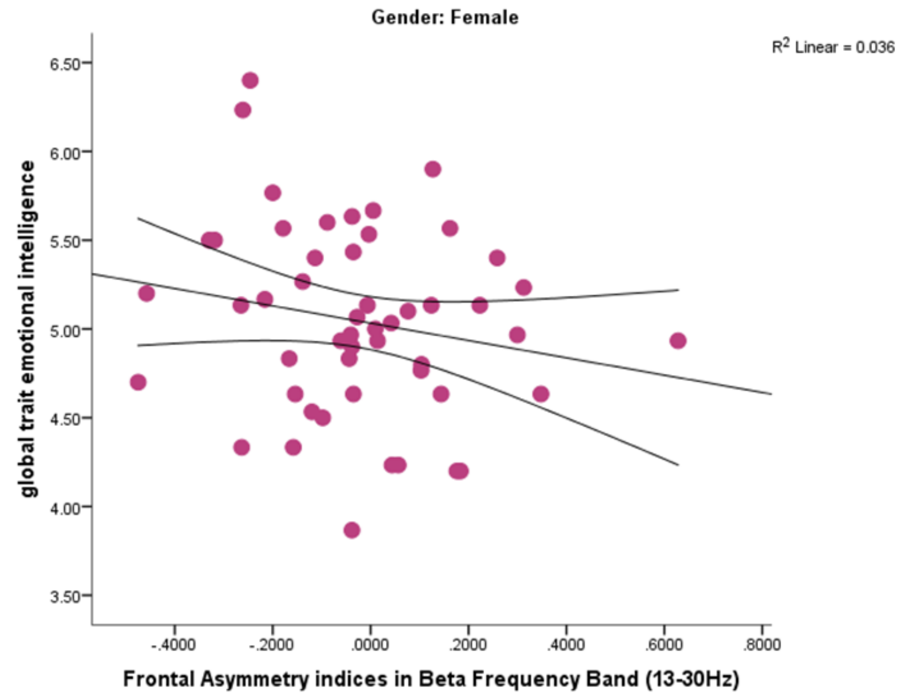
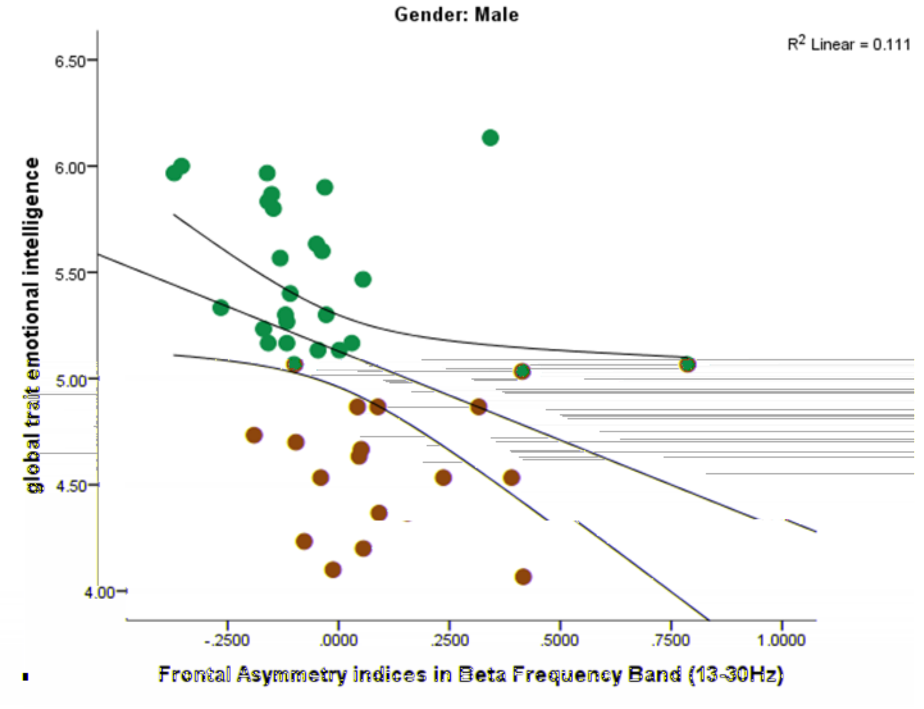
7. 2. 3. 3. Correlations when split by gender





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7. 2. 3. 4. Correlations between frontal asymmetry and dispositional flow and its subscales

		delta (1-4Hz)	theta (4-8Hz)	alpha (8-13Hz)	beta (13-30Hz)	gamma (30-45Hz)
Dispositional flow (DFS-2)	Pearson Correlation	-0.081	-0.043	-0.107	0.064	0.133
	Sig. (2-tailed)	0.450	0.692	0.317	0.552	0.215

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

[illegible]

Dispositional flow (DFS-2)	Pearson Correlation
	Sig. (2-tailed)

[illegible]

		delta (1-4Hz)	theta (4-8Hz)	alpha (8-13Hz)	beta (13-30Hz)	gamma (30-45Hz)
Flow in general life	Pearson Correlation	-0.219	-0.196	-0.041	-0.231	-0.254
	Sig. (2-tailed)	0.199	0.253	0.812	0.176	0.135
Flow in music listening	Pearson Correlation	-0.041	0.008	0.054	-0.036	-0.113
	Sig. (2-tailed)	0.810	0.963	0.751	0.830	0.505

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

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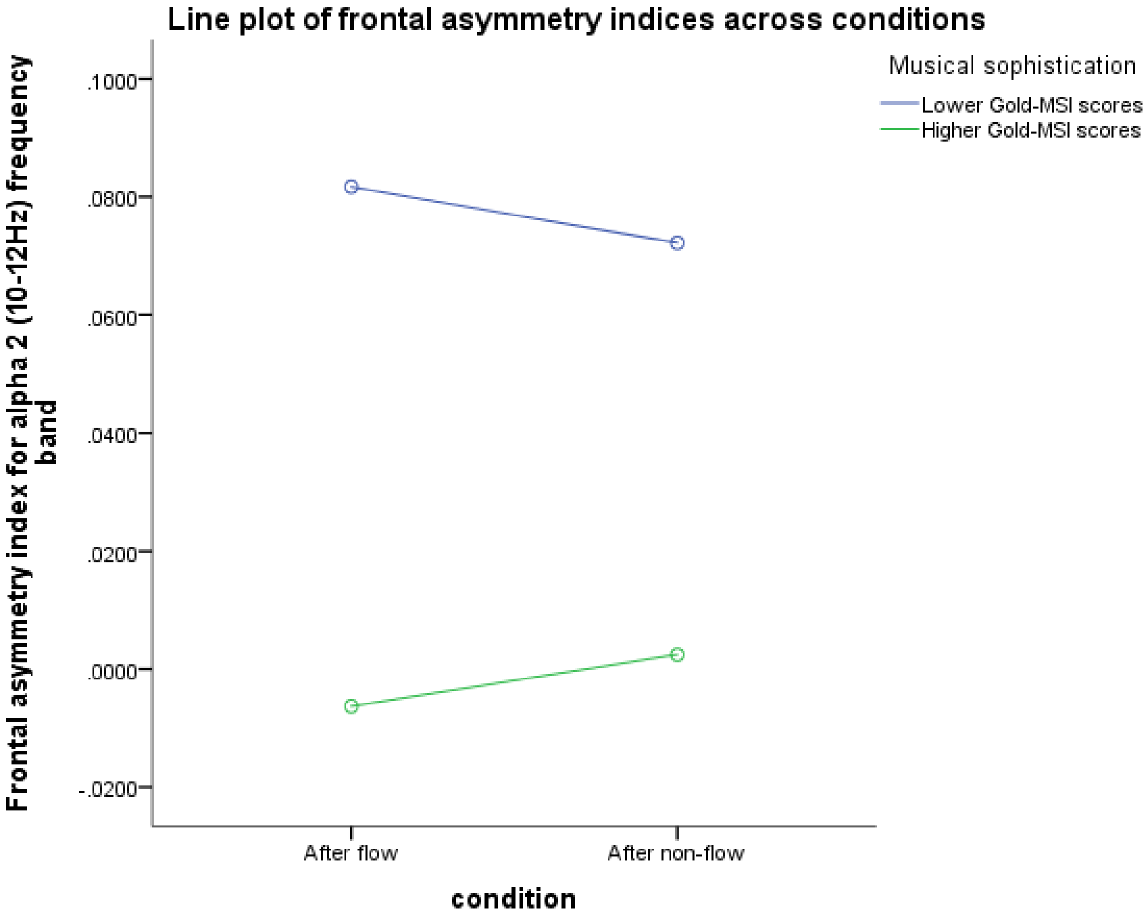
7. 2. 4. Interim discussion

7. 2. 5. Frontal asymmetry after playing

7. 2. 5. 1. Methods

7. 2. 5. 2. Results



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7. 2. 6. General Discussion

Chapter 8 Inducing flow with monaural beats

8. 1. Introduction

8. 1. 1. Auditory beat stimulation (ABS)

8. 1. 2. Flow in music listening

8. 2. Materials and Methods

Participants

8. 2. 2. Materials

8. 2. 3. Beat Stimuli

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8. 2. 4. Experimental Procedure

8. 2. 5. EEG Recording and Preprocessing

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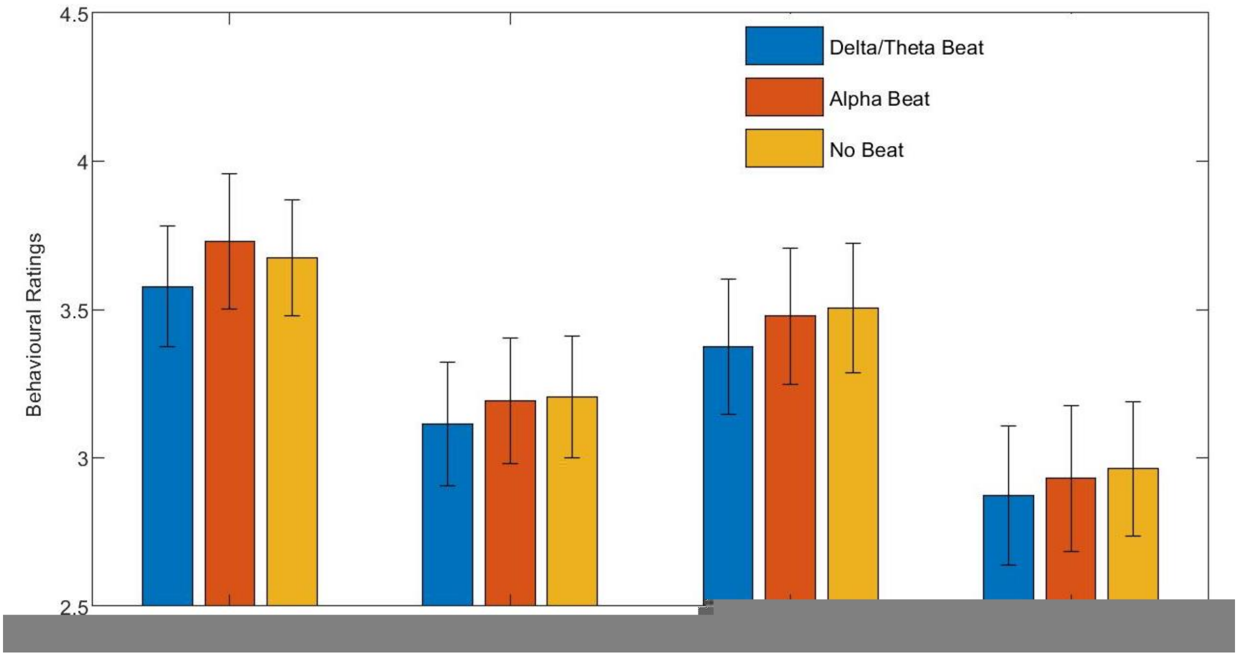
8. 2. 6. EEG Analysis

8. 2. 7. ECG Recording and Analysis

8. 3. Results

8. 3. 1. Behavioural Ratings



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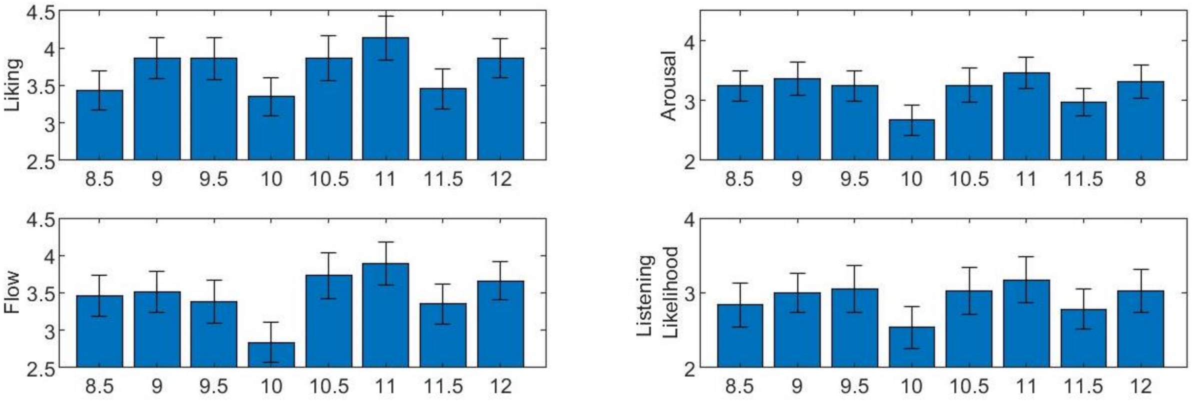

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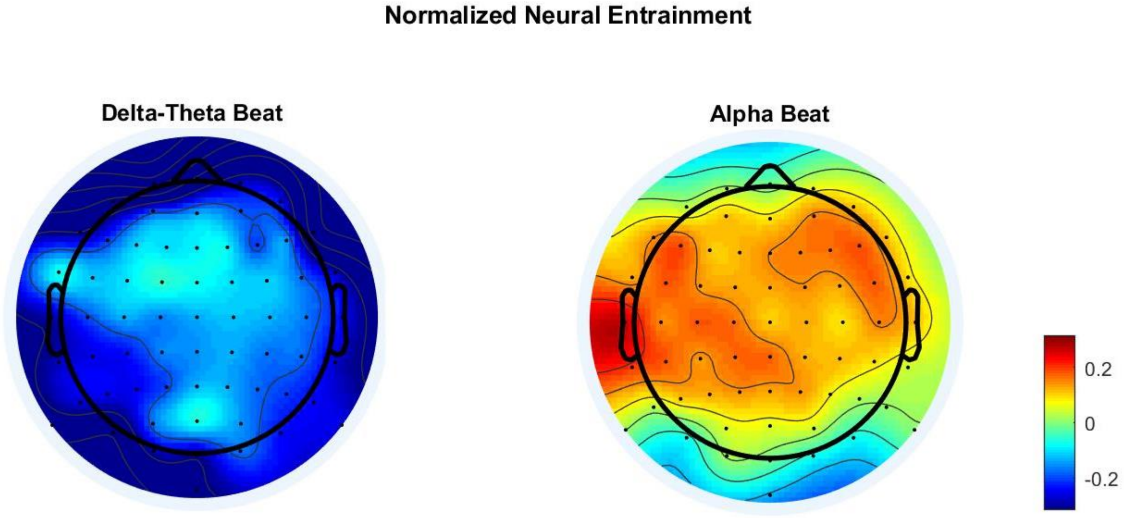
8. 3. 2. Neural: EEG Results



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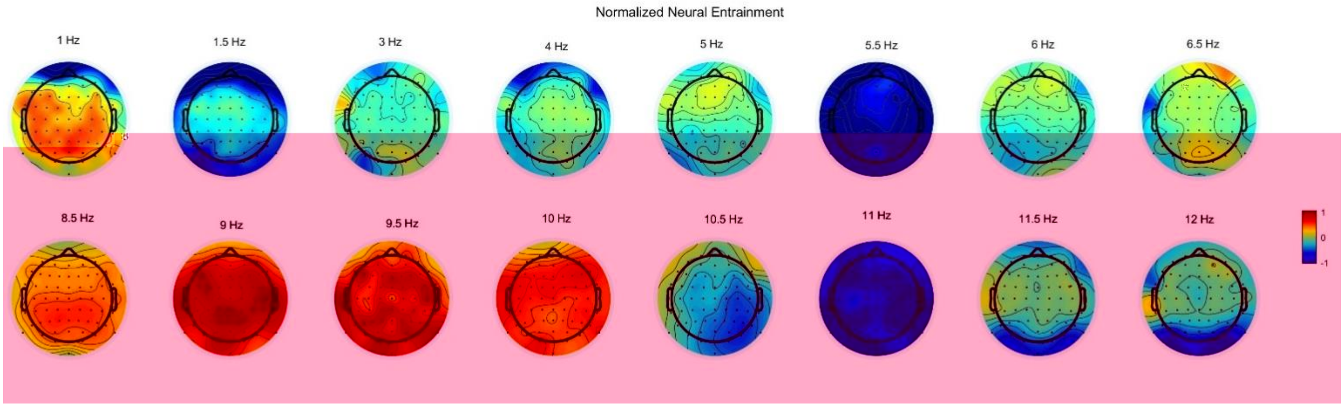
8. 3. 2. 1. Neural Entrainment and Neural Oscillations



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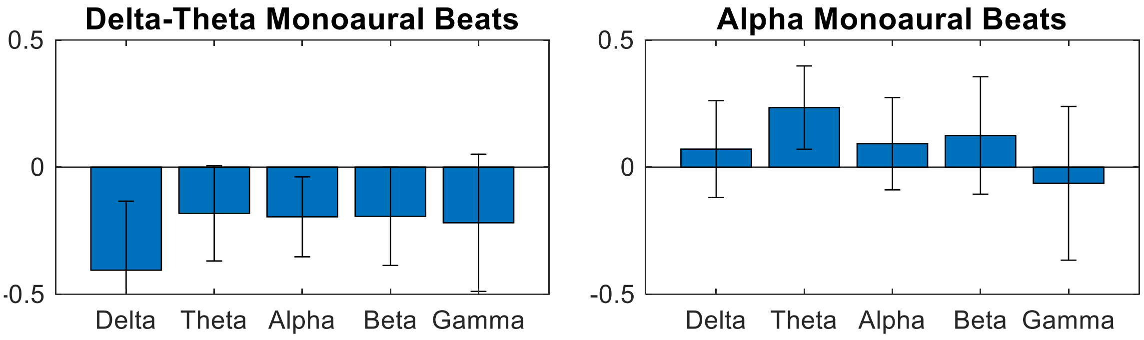

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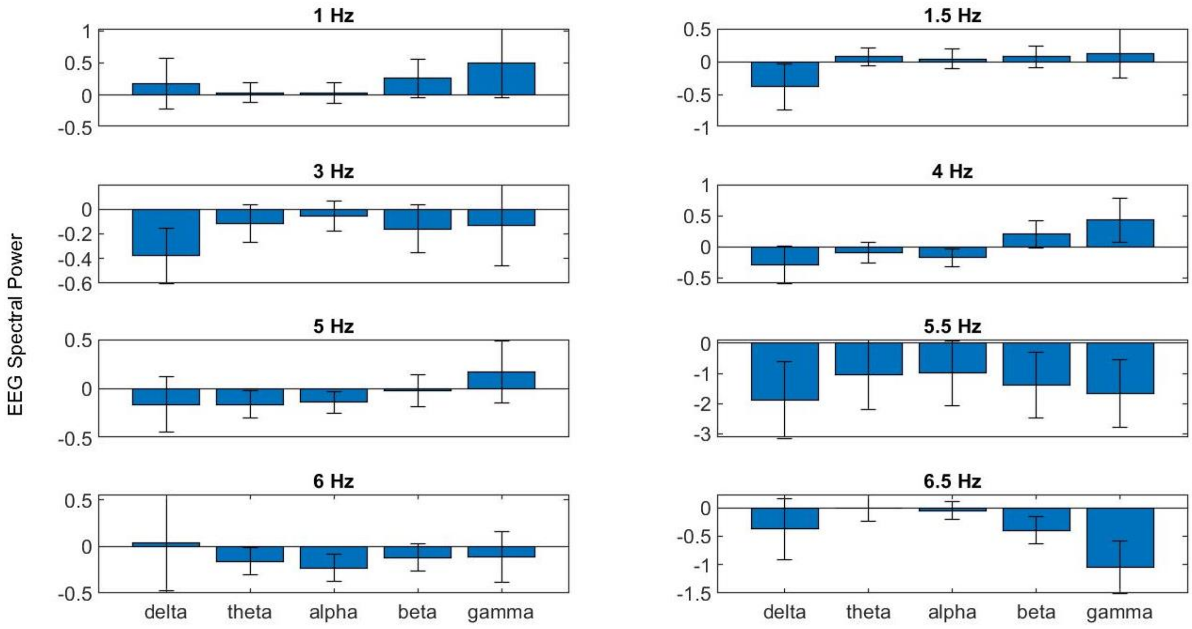

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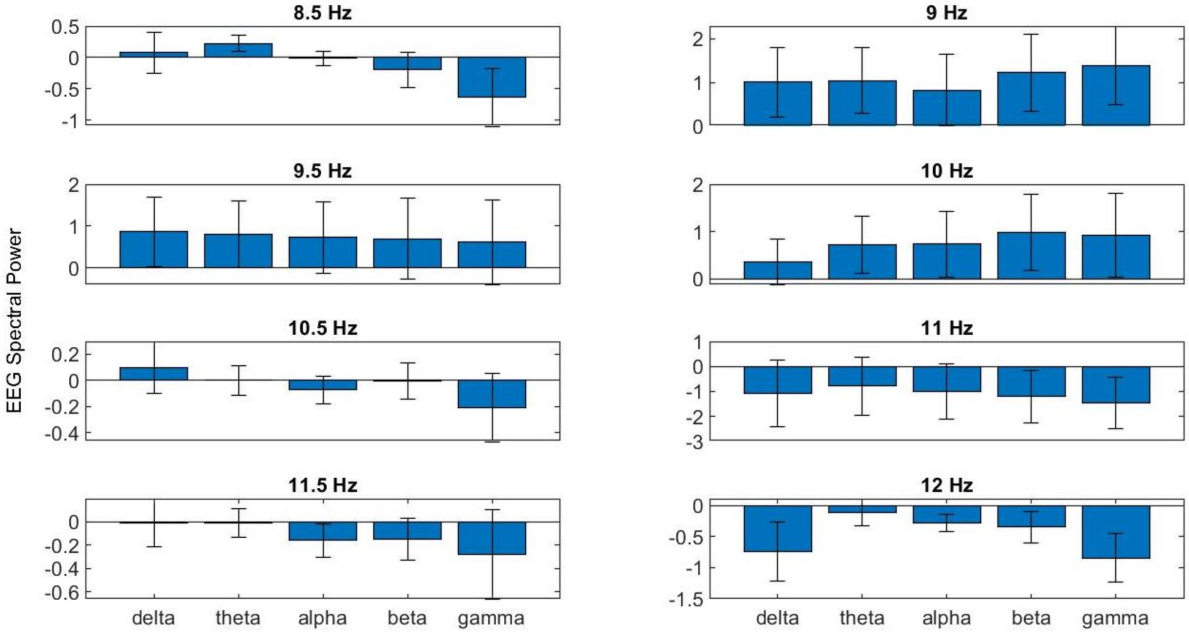

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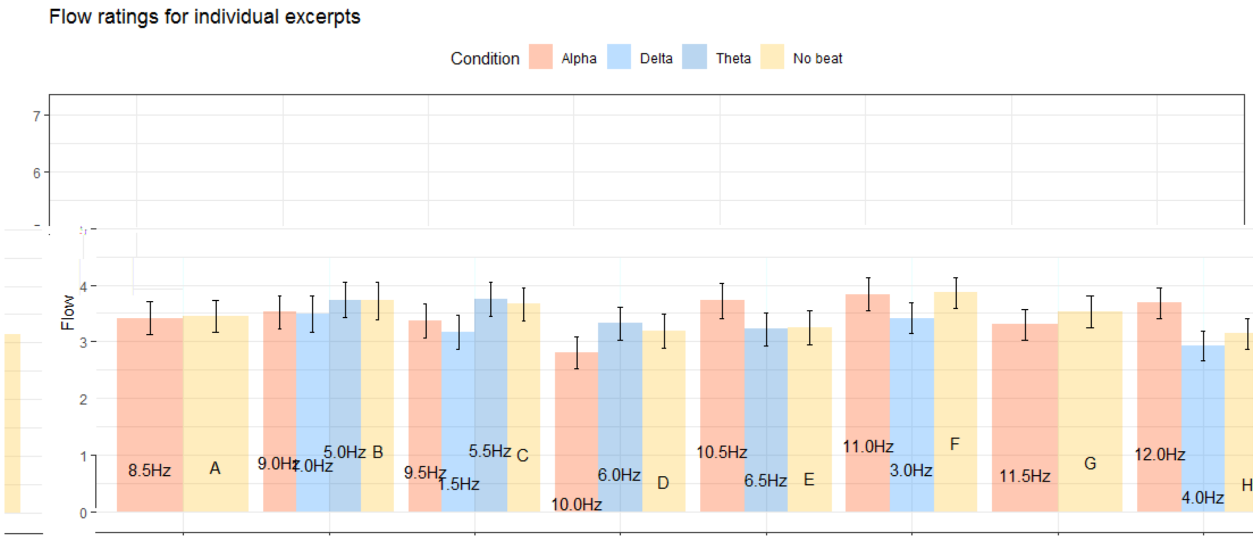
8. 3. 2. 2. Differences between high and low flow



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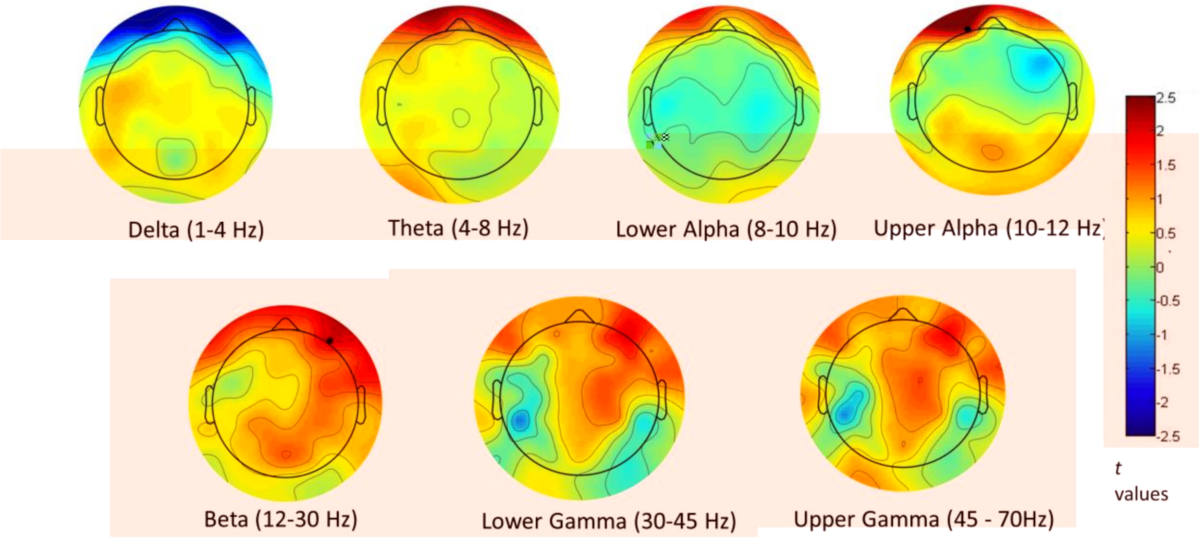

Delta (1-4 Hz)

Theta (4-8 Hz)

Lower Alpha (8-10 Hz)

Upper Alpha (10-12 Hz)

Beta (12-30 Hz)

Lower Gamma (30-45 Hz)

Upper Gamma (45 - 70Hz)

Topoplots of *t*-values by comparing EEG power of seven frequency bands between flow and non-flow states. Red indicates that power is higher in the flow condition while blue indicates that the power is higher in non-flow condition. Statistically significant electrodes ($p < .05$) are indicated by black dots.

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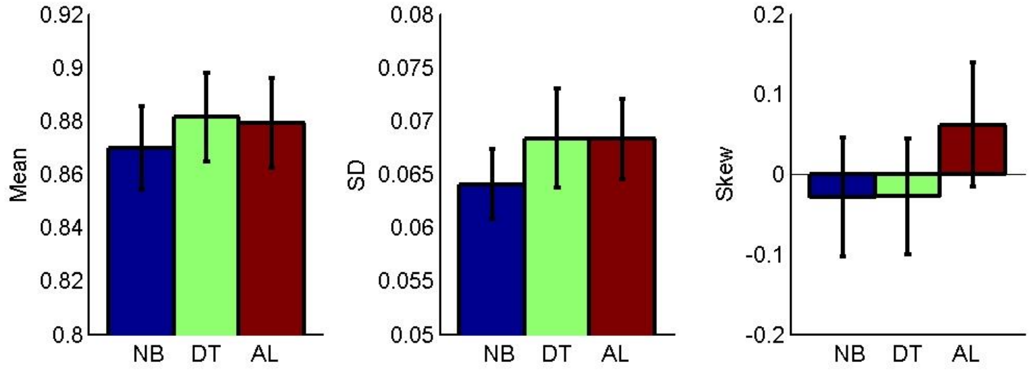
Autonomic: HRV Results



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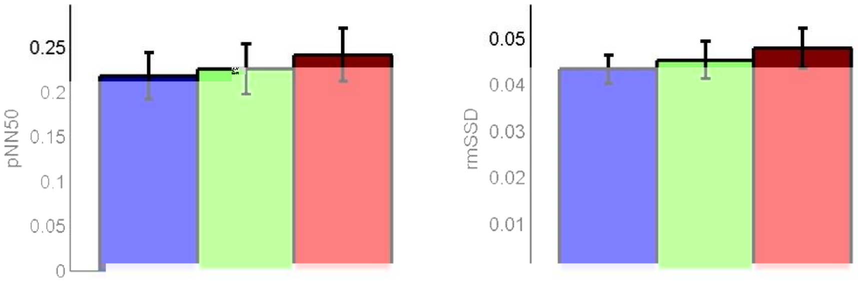

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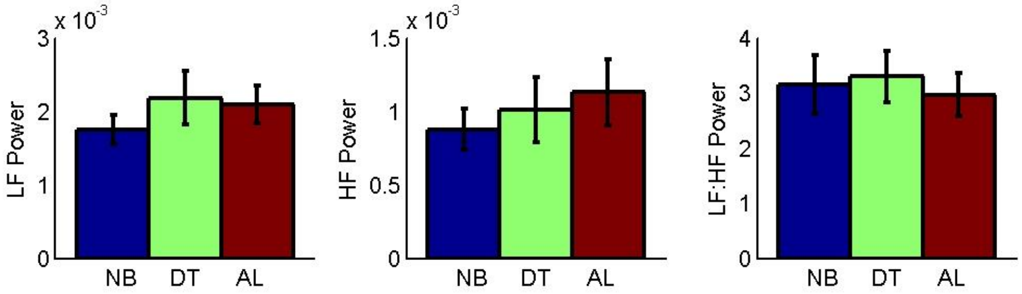

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8. 4. Discussion

8. 4. 1. Effects of monaural beats stimulation on flow experience

8. 4. 2. The neural correlates of flow in music listening

8. 4. 3. Monaural beats in music to aid flow

8. 4. 4. Conclusion

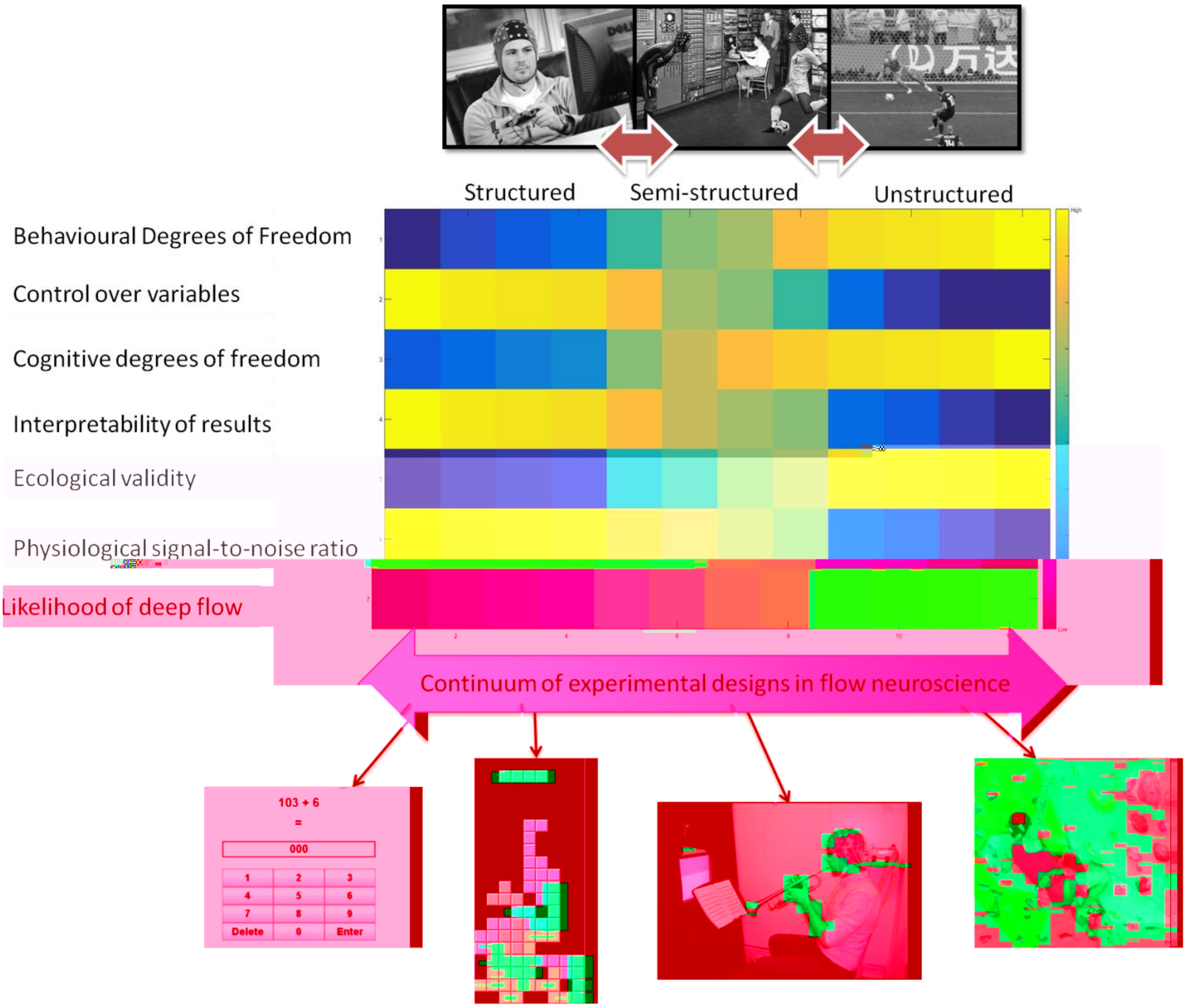
Chapter 9 Discussion

9. 1. Summary of findings

9. 2. Limitations

9. 3. The future of neuroscience of flow research

9. 3. 1. Scalable experiments



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9. 3. 2. A reliable way of identifying flow

9. 3. 3. Methods of flow induction

9. 3. 4. Hyperscanning

9. 4. Conclusion

References