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RESEARCH ARTICLE

The Complex Pre-Execution Stage of Auditory Cognitive Control: ERPs Evidence from Stroop Tasks

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Abstract

Cognitive control has been extensively studied from Event-Related Potential (ERP) point of view in visual modality using Stroop paradigms. Little work has been done in auditory Stroop paradigms, and inconsistent conclusions have been reported, especially on the conflict detection stage of cognitive control. This study investigated the early ERP components in an auditory Stroop paradigm, during which participants were asked to identify the volume of spoken words and ignore the word meanings. A series of significant ERP components were revealed that distinguished incongruent and congruent trials: two declined negative polarity waves (the N1 and the N2) and three declined positive polarity wave (the P1, the P2 and the P3) over the fronto-central area for the incongruent trials. These early ERP components imply that both a perceptual stage and an identification stage exist in the auditory Stroop effect. A 3-stage cognitive control model was thus proposed for a more detailed description of the human cognitive control mechanism in the auditory Stroop tasks.

Introduction

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et al.

Method

2.1 Participants

21 (10 11 , 21 2 , 22.8)

2.2 Stimuli and Task

2.3 Recording

Table 1. Stimulus List.

Stimuli (Word meaning)	Gender	Relative voice volume (dB)	Conditions
/Da/ (Loud voice)	male	0	Congruent
/Da/ (Loud voice)	male	-20	Incongruent
/Da/ (Loud voice)	female	0	Congruent
/Da/ (Loud voice)	female	-20	Incongruent
/Xiao/ (Low voice)	male	0	Incongruent
/Xiao/ (Low voice)	male	-20	Congruent
/Xiao/ (Low voice)	female	0	Incongruent
/Xiao/ (Low voice)	female	-20	Congruent

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2.4 Data Analysis

2.4.1 Offline EEG Data Analysis.

2.4.2 Statistical Analysis of the ERP data.

2.4.3 Behavior Data Analysis.

2.4.4 Topographic distributions Analysis. ( ), R 0 (1, 1, 2, 2, , - 1, - 2) .

Results

3.1 Behavior

1 . (0.00 % . 0.02 %, 0.022 , (20) , 0, < 0.001). R (R . . 18. , .0 , (20) . 12 , < 0.001).

3.2 ERPs

3.2.1 ERP components (P1, N1, P2, N2, P3 and Late-SW). 21 R 1, 1, 2, 2, - ( ). R 0 , 0 0 . R 2 . 2 R , . (-) . R ( ), ( ), ( ) 2 ( ) 00 1 , (2, 0 00) (2, 00 , 0) . , R (1, 200). 1 . - - . , 1 (1 0) . R (1, 1, 2, 2, -) . (,), R R . 2, - 1 0 200 00 0 - 0 . , -

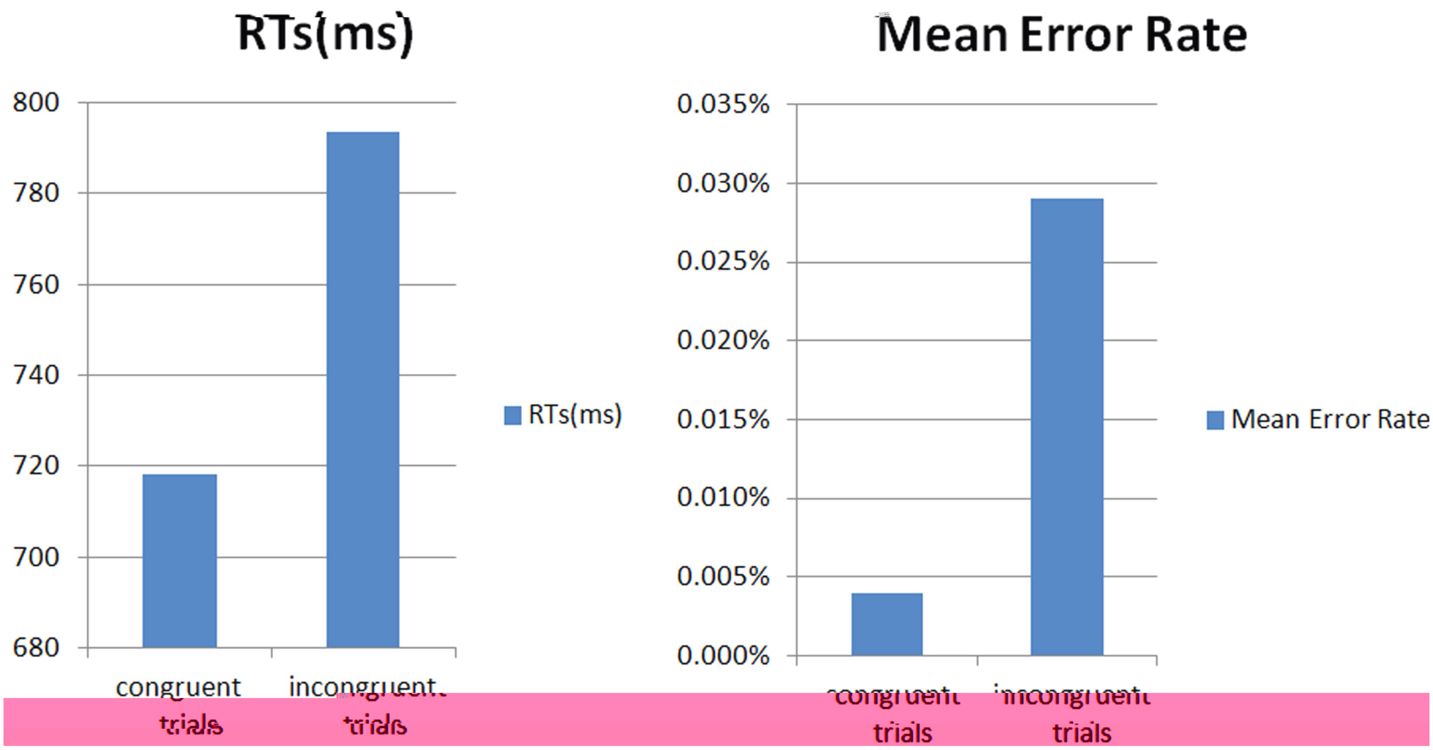

Fig 1. The behavior analysis results.

doi:10.1371/journal.pone.0137649.g001

3.2.2 Statistical Analyses. 2 R

(1 121 1 0

2 2 1 2 0 , 2 1 00 , 01 0 21 0),

(1 181 210

2 1 0 , 1 0 - 1 81 10 , 11 0 , 1 0 ,

1 00 , 01 0 , 1 0 , 1 0 - 1 1 20 , 21 0 ,

1 80).

(1 211 2 0 - 2

81 810).

i 1, 2, (1 2

) *j* , *j* 1, 2, , (1 1 2 2 -

) .

1 (121 1 0)

(2 F .02, p .02) (F . 1, p .01)

2 (2 1 0) 2

2 1 00 (1 F 18.1 , $p<0.001$ 2 F 20.88, $p<0.001$ F 2 . ,

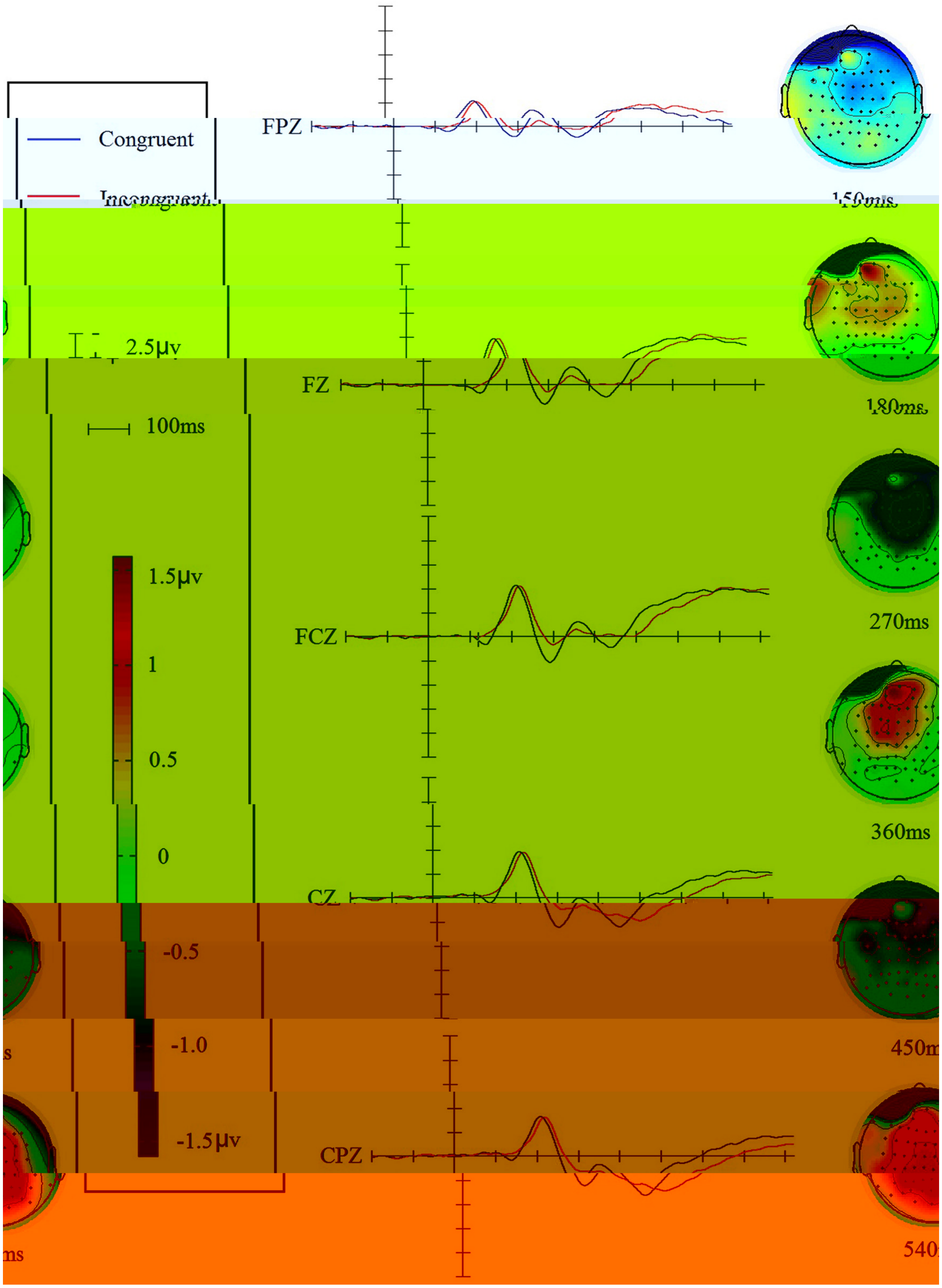

Fig 2. The grand-average ERP waveforms for the five adjacent midline electrodes (elicited by the incongruent stimuli and the congruent ones) and the topological distributions of such ERPs' modulations identified by the group averaged difference waves.

doi:10.1371/journal.pone.0137649.g002

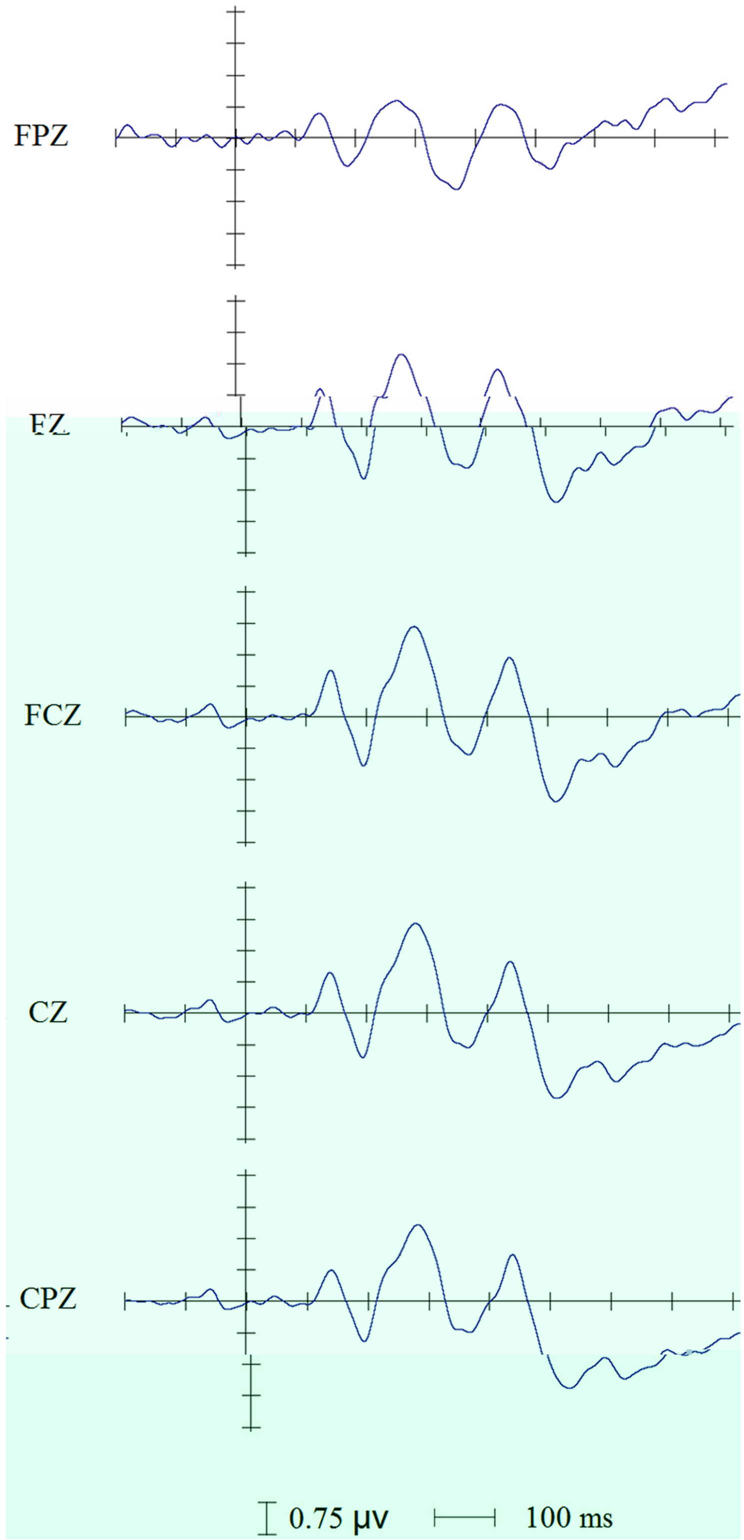

Fig 3. The group averaged difference waves (Incongruent minus Congruent) for the five adjacent midline electrodes showing the four modulations of the P1, the N1, the P2, the N2, the P3 and the Late-SW.

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Table 2. Summary of results from ANOVA conducted for post-stimulus ERPs.

Times (ms)	Trial Type	Trial Type *Laterality	Trial Type *Frontality	Trial Type *Laterality *Frontality
P1				
121~150	*F* = 5.6, *p* = .029	*F* = 8.3, *p* = .004	NS	NS
N1				
181~210	*F* = 10.4, *p* = .004	NS	NS	NS
211~240	*F* = 5.3, *p* = .032	NS	NS	NS
P2				
241~270	*F* = 19.4, *p*<0.001	NS	NS	NS
271~300	*F* = 21.3, *p*<0.001	*F* = 4.7, *p* = .021	NS	*F* = 2.7, *p* = .016
301~330	NS	*F* = 3.6, *p* = .042	NS	NS
N2				
331~360	*F* = 4.3, *p* = .05	NS	NS	*F* = 2.4, *p* = .032
361~390	NS	NS	NS	*F* = 2.6, *p* = .026
P3				
421~450	*F* = 7.4, *p* = .013	NS	NS	NS
Late-SW1				
481~510	*F* = 20.4, *p*<0.001	NS	NS	NS
511~540	*F* = 39.6, *p*<0.001	NS	NS	NS
541~570	*F* = 18.8, *p*<0.001	NS	NS	NS
571~600	*F* = 24.8, *p*<0.001	NS	NS	NS
601~630	*F* = 21.3, *p*<0.001	NS	*F* = 6.9, *p* = .004	NS
631~660	*F* = 9.7, *p* = .006	NS	*F* = 8.3, *p* = .003	NS
661~690	*F* = 7.1, *p* = .015	NS	*F* = 14.1, *p*<0.001	NS
Late-SW2				
691~720	NS	NS	*F* = 23.7, *p*<0.001	NS
721~750	NS	NS	*F* = 12.0, *p* = .001	NS
751~780	NS	NS	*F* = 16.1, *p*<0.001	NS
781~810	NS	NS	*F* = 14.6, *p*<0.001	NS

*: the interaction between two factors or among three ones;
NS: not significant.

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$p<0.001$) 1 1 F 1 . . , p .001 1 2 F 1 . 1, $p<0.001$ 1 F 1 .2 , $p<0.001$ 1 F 1 .1 , p .001 2 1 F 1 .8 , p .001 2 2 F 20. . , $p<0.001$ 2 F 22.1 , $p<0.001$ 2 F 20. , $p<0.001$ 1 F 1 . , $p<0.001$ 2 F 2 . , $p<0.001$ F 2 . 2, $p<0.001$ F 18. 0, $p<0.001$

2 (1 0) 1 0 (1 1 F . 8, p .020 1 2 F .0 , p .02 2 1 F . 0, p .0 1 1 F .8 , p .0 0) 1 0 (1 1 F . 1, p .021 1 2 F .21, p .022 2 1 F .0 , p .02) , 1 0 (1 F . , p .02) 1 0 (1 F .1 , p .0) -

- 1 (01 0) 01 0 (F 21. . , $p<0.001$ F , $p<0.001$) 0 0 (F 10.2 , p .00 F 2 . . , $p<0.001$) 1 0 (F . , p .012

Table 3. Summary results of simple effect analyses.

Times (ms)	Trial Type *Laterality	Trial Type *Frontality	Trial Type *Laterality *Frontality
P1:			
121~150	L2: $F = 6.02, p = .023$		
	L3: $F = 7.31$, $p = .014$		
P2:			
271~300	L1: $F = 18.17$, $p<0.001$		L1A1: $F = 15.46, p = .001$
	L2: $F = 20.88$, $p<0.001$		L1A2: $F = 17.41, p < .001$
	L3: $F = 23.75$, $p<0.001$		L1A3: $F = 19.25, p < .001$
			L1A4: $F = 15.13, p = .001$
			L2A1: $F = 14.87, p = .001$
			L2A2: $F = 20.49, p < .001$
			L2A3: $F = 22.13, p < .001$
			L2A4: $F = 20.93, p < .001$
			L3A1: $F = 17.93, p < .001$
			L3A2: $F = 27.95, p < .001$
			L3A3: $F = 26.32, p < .001$
			L3A4: $F = 18.50, p < .001$
301~330	NS		NS
N2:			
331~360			L1A1: $F = 6.38$, $p = .020$
			L1A2: $F = 6.06$, $p = .023$
			L1A3: $F = 5.55$, $p = .029$
			L2A1: $F = 5.40$, $p = .031$
			L3A1: $F = 4.84$, $p = .040$
361~390			L1A1: $F = 6.31$, $p = .021$
			L1A2: $F = 6.21$, $p = .022$
			L2A1: $F = 6.05$, $p = .023$
			L1A3: $F = 5.13$, $p = .035$
Late-SW1:			
601~630		A1: $F = 9.60$, $p = .006$	
		A2: $F = 11.37$, $p = .003$	
		A3: $F = 21.76$, $p<0.001$	
		A4: $F = 44.97$, $p<0.001$	
631~660		A3: $F = 10.25$, $p = .004$	
		A4: $F = 26.56$, $p<0.001$	
661~690		A3: $F = 7.67$, $p = .012$	
		A4: $F = 25.87$, $p<0.001$	
Late-SW2:			
691~720		A4: $F = 19.45$, $p<0.001$	
721~750		A4: $F = 12.50$, $p = .002$	
751~780		A4: $F = 8.97$, $p = .007$	
781~810		A4: $F = 4.80$, $p = .041$	

*: the interaction between two factors or among three ones;

NS: not significant.

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F 2 .8 , $p<0.001$) 01 0 (1 F . 0, p .00 2 F 11. , p .00)

- 2 (1 810)
1 20 (F 1. , $p<0.001$) 21 0 (F 12. 0, p .002) 1 80 (F 8. , p .00) 81 810 (F .80, p .0 1) -

0 R R -

2 1

3.2.3 Brain Electrical Activity Mapping.

R (1, 1, 2, 2,) - 2 -

Discussion

4.1 Behavior

4.2 ERPs

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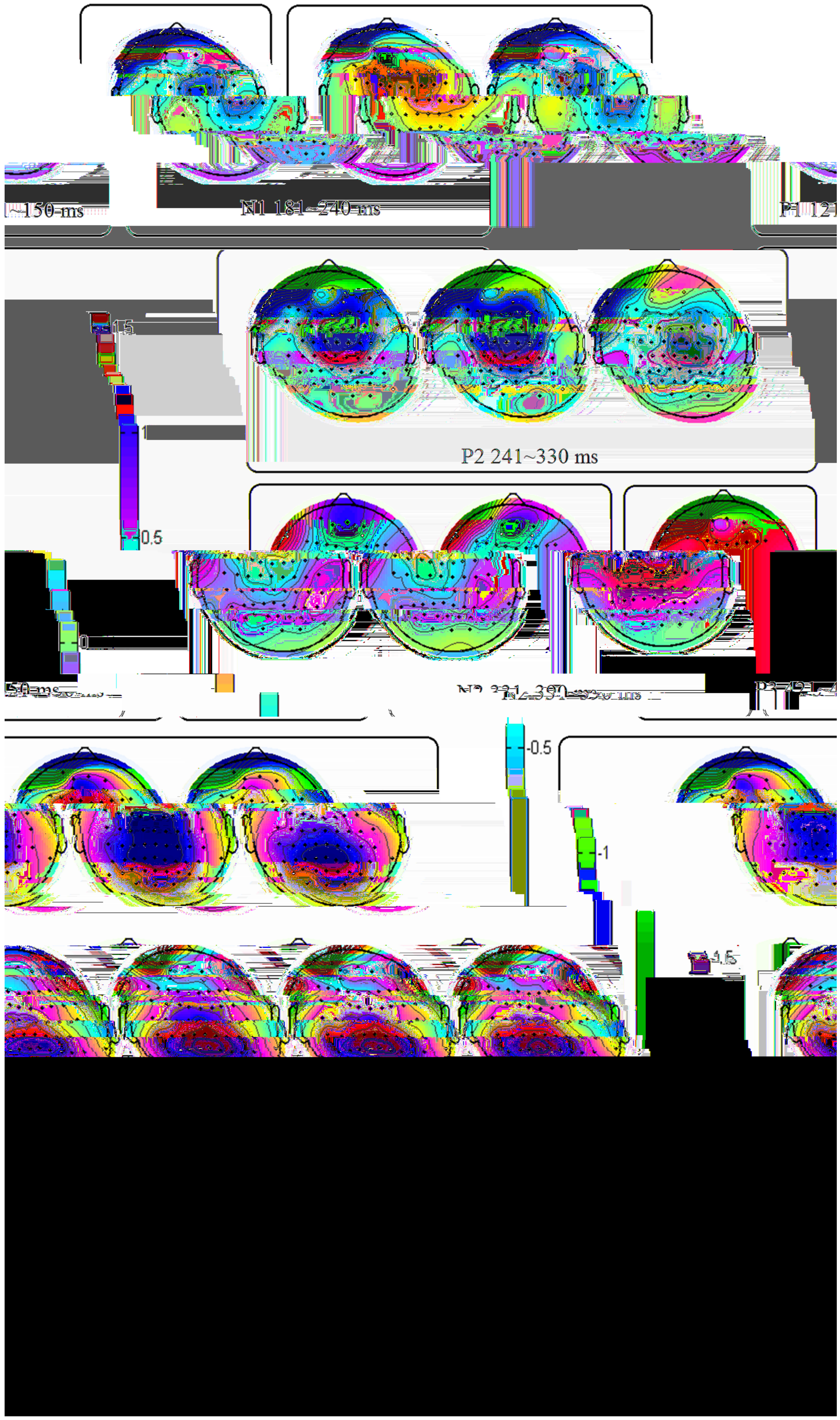

Fig 4. Brain electrical activity mapping (incongruent minus congruent) for the mean amplitude values of each 30 ms time window at around the seven ERP components (P1, N1, P2, N2, P3, Late-SW1, Late-SW2).

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4.2.1 Pre-execution Components' Effects.

Identification Components'

4.2.2 Executive Components' Modulation: the Late-SW.

4.2.3 Analysis strategies and experimental factors in obtaining different results in the pre-execution ERP components or response conflict effect.

4.3 Model of the Auditory Stroop Task

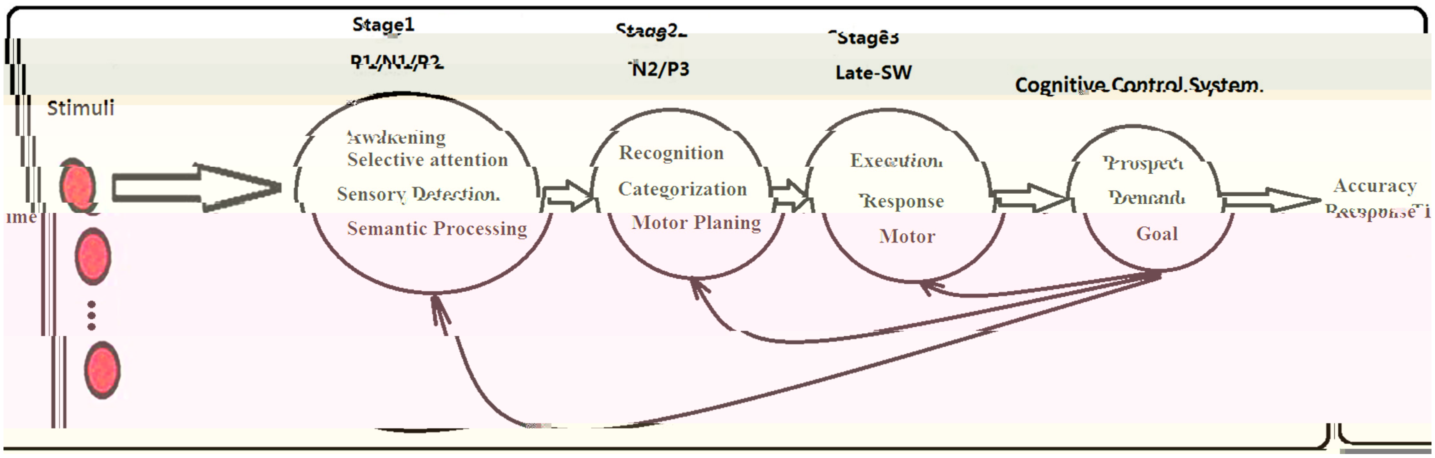

Fig 5. The three stages cognitive control model for auditory Stroop task.

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Conclusion

[illegible]

Acknowledgments

[illegible]

Author Contributions

[illegible]

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