

This article was downloaded by:[CDL Journals Account]
On: 1 March 2008
Access Details: [subscription number 789921172]
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954
Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Progress in Natural Science

Publication details, including instructions for authors and subscription information:
<http://www.informaworld.com/smpp/title~content=t713724104>

Feature combination for classifying single-trial ECoG during motor imagery of different sessions

Wei Quigguo^{ab}; Meng Fei^a; Wang Yijun^a; Gao Xiaorong^a; Goa Shangkai^a

^a Department of Biomedical Engineering, School of Medicine, Tsinghua University, Beijing, China

^b Department of Electronic Engineering, School of Information, Nanchang University, Nanchang, China

Online Publication Date: 01 July 2007

To cite this Article: Quigguo, Wei, Fei, Meng, Yijun, Wang, Xiaorong, Gao and Shangkai, Goa (2007) 'Feature combination for classifying single-trial ECoG during motor imagery of different sessions', Progress in Natural Science, 17:7, 851 - 858
To link to this article: DOI: 10.1080/10002007088537482

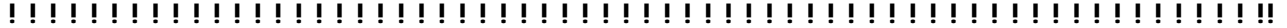
URL: <http://dx.doi.org/10.1080/10002007088537482>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article maybe used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

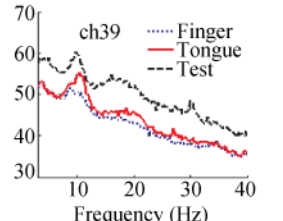
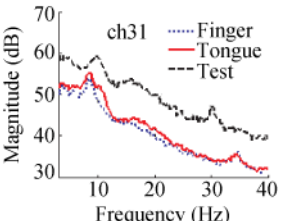
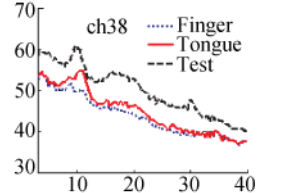
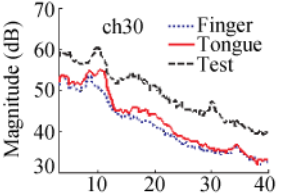
The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.



! "#\$%&'()*

" #&' (%) * (" #& " # ' +, -.) (, / 0 1 2 3 4 5 6 7 8 9 : ; < = > ? @ A B C D E F G H I J K L M N O P Q R S T U V W X Y Z [\] ^ _ ` { | } ~

E# G>. %') 6"# /0%(" ,) 4/" .") ("%G. % "#\$ " # "G(. (5%" S2"" %%" , \$4 6 4 260(" %%%) (%*." # S2-") (' *' 'G. (&" *' (: E#% , "# ,) 0%) (2(5 88 (%S" %4\$ 260. H5: I) % *% "# S305 2S4/7-2 % , "G) 6S7" OS7(6) 4 ' \$ # "SG(4)) 0. 4S50) 6' . "# 076 7" 7 6(50) 0) (5'). ("# "G(. (5%" S2(6) 4 &" # "SG((" # "" %%") (. (232 S7, #S(' % J. (, ' # , -G 6 4 "# "" %%" . %"# S305 2S4/7-2 % , "G) 6"# *) "SG. ." # -27 &" *' ("# *) , -G(6) 4 "# "G(. (5%" . 6"# %& , " %&S(%S" 22 () " , #S(5 : L) *' 30, \$9%) * (. (" # %650 , "# S31 05 2S4/7-2 % , " 0 4) 6"" %%" . %60S2 3 "#S) 6"# "G(. (5%" : E#% 4/7 %"#S " # &S(%S") 6"# %& , " 30 2 %5. 6 S(" 7 6) 4 "# "G(. (5 %%%) (") "# "" %%%) (:



H5: I: E# S305 2 4S(-2 % , "G) 6S7" OS7(6) 4 ' \$ # "SG(4)) 0. 4S50) 6' . "# 076 7" 7 6(50) 0) (5'). ("# "G(. (5%" S2(6) 4 &" # "SG((" # "" %%") (. (232 S7, #S(' % J. (, ' # , -G 6 4 "# "" %%" . %"# S305 2 4S(-2 % , "G) 6"# *) "SG. ." # -27 &" *' ("# *) , -G(6) 4 "# "G(. (5%" . 6"# %& , " %&S(%S" 22 () " , #S(5 : L) *' 30, \$9%) * (. (" # %650 , "# S31 05 2S4/7-2 % , " 0 4) 6"" %%" . %60S2 3 "#S) 6"# "G(. (5%" : E#% 4/7 %"#S " # &S(%S") 6"# %& , " 30 2 %5. 6 S(" 7 6) 4 "# "G(. (5 %%%) (") "# "" %%%) (:

MO.) (%2G.) (60"#% / 0 & 4 * %6. . 6"# %\$S. \$7 2% 0 & .) () 6 &S(' 7, " 0, \$: . 3" >) 6"#

%& , " 22 () " , #S(5 . ("# " *) %%%) (% , * . "# "# %7 . (0 \$) 02 , 0 \$. (4S(-2 , "# %45# ()) % \$ % 0 - % 0 & 4 : E#% , "# 677 * . (5 \$ \$7 % 8 * % 88 2) ("# % 9 % 4 .) (S2 . "% 372 > % - 72 & ,) (604 2 & "# 0 % 7) 6"# \$ \$7 % 8 E# . 41 / \$) 6"# 4S(-2 , #S(5) (, 7 % 6 , \$.) (, \$ & \$7 3 \$ 2 &) 04 \$ 7 . (5"# 6 \$ - 0 % - % 260 , 7 % 61 , \$.) (! (\$22) (, "# ,) 4 & (\$.) () 6 4 7 . 7 6 \$ 1 - 0 % 45# ,) (" 0 & " ") . (0 \$ (5 , 7 % 6 , \$.) (\$ 1 , - G > :

MO / 0 , ' 20 %) 6 , 7 % 6 . (5 % (57 10 \$ @) B 0 .) 0 2 2 0 (5 4)) 0 4 S 5 0) 6"# 7 6 7" 7 6 (5 0) 0" (5' * . "# % % %) (I) P % %) (" G (6 0 S 0 % 4 4 S I 0 7 2 . (H5: N: ! " ,) (% % % 6"# 677 * . (5 % / % :

I) E# 4 7 , #S(' 7 @) B * % 0 / 0 , ' % 2 & 0 2 , . (5"# % 4 / 7 (5 G) , % 7 , . (5 \$ % " 8 8 7 0 6 0 ' (, ' S2 . (" Q' / . (5"# \$ 0 . 0 2 % 0 ' (, ; :

N) " *) 260 (" 60' (, > 88 2 % * ' 0 % 7 , " 2)) & \$ (; < = S2 @ A % 5 (\$ % % (57 * / % P Q L ?) S2 8 8 2 / % C Q L ?) 67 0 0 % , " 3 7 ; :

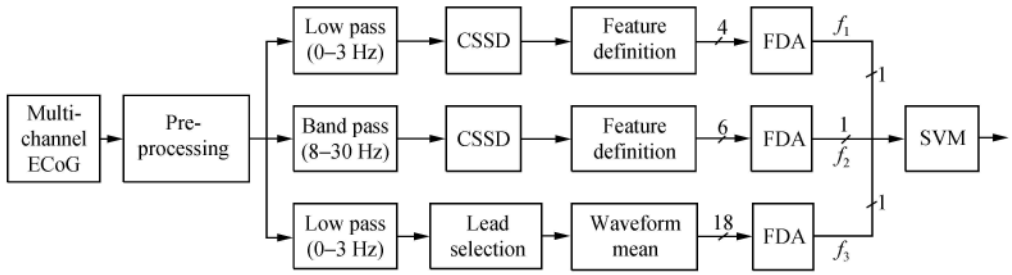
Q) "# 0' 6 \$ - 0 % * ' 0 ' + " G " 26 4 "# S2 3 *) 60' (, > 88 2 % E *) 6 \$ - 0 % * ' 0 2 0 3 2 & ,) 4 4 (% \$. \$ 7 % 8 \$ ' 2 ,) 4) % .) ((FJJA) S2 HP # 0 2 % 0 4 (\$ " \$ \$7 % 8 (HAR) , S2 "# "# 0 2) (' * %) & \$ (2 6 4 "# 4 ' \$ 3 7) 6 % 4 / 7 .) (% \$ 2 HAR ; :

S) "# % "# 0' 6 \$ - 0 % * ' 0 ,) (, \$' (\$' 2 \$ 2 6 2 . (") \$ 7 (\$ 0 % /) 0 3 ,) 0 4 \$ # (' (JT ;) 60 , 7 % 6 , \$.) (:

@ \$ #) 6"# % % % / % 2 % - % 2 . (4 0 2 " \$ 7 . ("# 677 * . (5 % .) (%

I : I A \$ \$ \$ 0 . %) (S2 / 0 / 0 , ' % 5

A 0 (5 "# UF! ' + / 0 4' (" , \$ % & , " # S2 ") / 0 0 4 . 4 S (' 2 4) 3 4' (" % 6' . "# 076 % 4 S 7 6 (1 5 0) 0" (5' : E# ' 7, " 0, \$ 7 8 8 (\$: . 3' . % * ' 0 ,) 7 7 , " 2 2 0 (5"# % " OS % - % (5 \$ (CVC @) B / 8 1 . (- 4 ' 7, " 0 2 5 0 2 * # , # * % 7 8 ' 2) ("# ,) (" OS 1 ' OS (0 5 #) 4)) 0 ,) 0' + : @ \$ # " OS * \$ 0 ,) 0 2 6 0 Q 2 G .) (S2 \$ 7 0 ,) 0 2 (5 * ' 0 / 0 0 4 2 * . "# \$ % 4 / 7 (5 G)) 6 I HP L ? : R 3 ' 0 \$ 4 / 7 6 , \$.) ("# 0 ,) 0 2 1" (" . \$ % * ' 0 % 0 2 % 4 , 0 3 7 3 7' % E# 5 3 (2 5 % " . (, 7 2 % S " G . (5 %)) 6 NC " OS % * . "# 7 8 7 % S 2 \$ (- (7 8 & 7 2 " % %)) 6 I HP " OS % R 2 " \$ 7 2 2 % 0 / .) () 6"# A \$ \$ J " ! . (UF! F) 4 / " 1 ") (!!! , \$ & 6 - (2 . ([QW] :

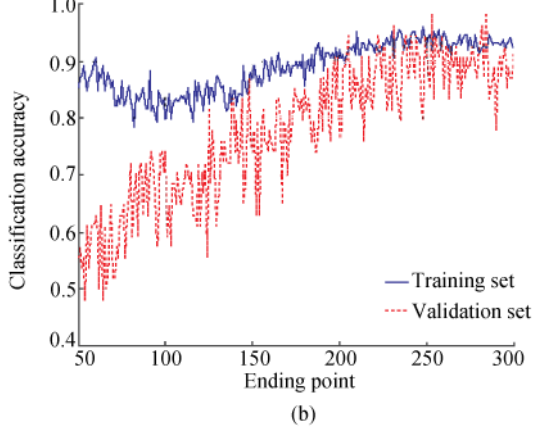
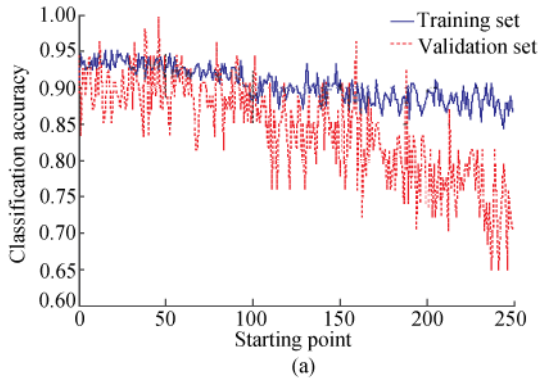


!"#%\$ &0*+ ,*(.)0-"12#-"2#3'0'56(7+,"2#8(4"80#1(. :4'4#."2#('42#*94-*-"(23'3%-"(2402.*'S

;:* #<248*-*!"- =>>> -08?*'("24 ?'
4"0'S@('+' 4-Q*)(8?;4#(20/10 Q2+'*+)*
4*'*A""8*24('8*8'1,0/4022#Q2+4-44"3
Q'9*'+(9208?'+4 =>> ?"24 B1+)*"80#(2S
;(*2Q)*4*+.,**2*-B*49*24*4 49(4C
Q2+'*+)*4*..*)4(.0404.) (88(2Q*0#
'*'*2*(6DE)^[E] 90,-*+4'*3*'*2*4*'*3
-08?'++0DS

D48'9'2(9'90 Q?)'+4 "24")*744*+00
-*#8*24.'(84*F44 %64 ?"24.(.,'4*
001"-SD-:(92"2!"#S=,4*)0-")Q(27*3
(80)*+*7*2, ?(24*-**)4(2(.+00-*#8*24
,-*+.(.)0-")Q(2S!"#S(0)-:(94*'*Q(23
-:"?B*49*2)0-")Q(20), '01(.!%Q'!*!
%+3
."2*+24*(./9'2#-*)4(2)Q2+4*-D42#?"24
(.48*9'2(9.(001"-,9."*4*2*2#?"24"-
."H+Q=>>S!"#S=(B)"/,40#4*'*Q(2:"?
B*49*2)0-")Q(20), '01(.!%Q2+4*2*2#
?"24(.4*48*9'2(9,9."*4*-D42#?"24"-
."H+Q(FS);:* ("#20/4022#-*490'Q2(81
-?4"24-,B*4.(4022#Q2+Q+Q(2S);:*"#B
, '*+*8(240#4Q)0-")Q(20), '01"2'*0-
8(242)0/1944*^2#4(.48*9'2(9"H*24
Q14*B'#222#Q2+2*2#704(.4*+00S@)/3
-"(2(.4*49(704(.+00(F4^[E]=A?"24('
%6F4^[E]=A?"24)9,(4800*)0-")Q(20), '03
)1+)*'0*Q2, 24B*SI*2*4*48*-*!%(.
%86?"24(F4^[E]%64?"24)9*);:(*2.(.'*Q
4*'*H404(24*2, '*:"#)0-")Q(20), '01S
F8% !*Q'!*H404(2

!*Q'!*H404(2-0),)0-4? "270#2'
'*)(#24(2S;:*)0-")Q(27.(80)*8021
+*7*2(29.'4*(2*H4044*8(-4+)"8'23
4*2'(80#(2S@0-"2#*.Q'!*+(*240:"*
-Q.04'1)0-")Q(2*,'A,-*'*0.'Q'*)Q2
B*)(8B2+4"8?(<*4*)0-")Q(27.(80)*
?(<+*4014*10*840/1"2*?2*21S



!"#S=S(0);:*'Q(2:'?(.)0-")Q(20), '01(.!%Q'!*!
!%Q2+4*-D42#?"24(+00.4*2*2#?"24"-."H+Q=>>);
(B)4*'*Q(2:'?(.4*)0-")Q(20), '01(.!%Q'!*!
%Q2+4*2*2#?"24(+00.4*-D42#?"24"-."H+Q(F)S;:* ("#3
20/4022#*490'Q2(81-?4"24-,B*4.(4022#Q2+Q3
+Q(2S

D4(,#JE&Q25EK ("#20# "2-"8'0
)('4)0'##(2Q2-:0*-(8*)(88(248'2#.*Q3
4'-,4""80#24+*Q2-7010+'4'B4(20*+'3
.*'24.'(8*0:(4*^[L]S;:"- ,##-44Q14*
49(.Q'!*0*2*?2*2#21S;:-,4"")(8B23
4(2)Q2?(<+*)(8?*'8*201"2'(80#(202)(23
-A*241*2Q2)0-")Q(27.(80)*S
;:*(./9'2#.(-'4?9*,-*+4*H404
.*Q'!*F:

F);:*?7?0*-*+009*'*1970-(>□=

!!

!")#8&(') & *+&S . /O 12,% ;

3)84 5,- *#. /O 12,% 61(' 5*7) & S8 9', 1 84 12,% 9#(' -9 + 86' - 84 86* & 1 1 ;

;)86* k, &%#8&(1 6(' 185, &) = >??@ AS 2& SS 2), & ,,-) , <<8) & 84), & *+&S') #*5 84 <(' 7AI R< & ' Bx Q' 9' 5<*- ' - & 1 ('%&) & ', 94& 1 ;

C)#, &A' 1 6(') ' #S') * - 84 +, 11 # # 1A9 9 5<*- ' - & 1, -) <(' D9&) * - & * - ') S5 - 13 - = ECF & 2 & #, &A' ! cH

I 4 <(*9) A' & ' Bx Q' 9' 5<*- ' - & 1 1 (' 19S') + %6 HI 6*) #(' - & 9 2 SS 7 & 1 1, S5, 25') 5*7 5 - & 1 # # ' 84 (% 8 % 82 # 2 ((& 1 F) * (& - 2A (& 1 J), 6(' 9 -) A&) AS 2 & ' B' (S5 - & HI' - 9 , & 4(' , ()) #(' - & : S) 1 # S 8 # (5 8 - ' 5 +))) S & 4 K * L), & ' & # 1 k' 9 8 9 & & 1 F * (& 1 J, -) & # 1 9 55* - & 84 86* & 1 1 \$ 9A \$ 2 - * S I H 4 AI & 4 5 A 8 9 4 -- '% K > * L 12, % ! F (# * 5 & 1 F), -) ! J (# * 5 & 1 J) 9 - + 5*) % , 1

$$!_F \text{ " } [\#_F \#_> \begin{Bmatrix} \$_F \\ \$_> \end{Bmatrix}] \quad (G)$$

$$!_J \text{ " } [\#_J \#_> \begin{Bmatrix} \$_J \\ \$_> \end{Bmatrix}] \quad (3)$$

64(' \$F, -) \$J, (' & 1A9 1 k' 9 8 9 & & 1 F , -) & 1 J (' k' 9 8 7 % # F, -) # J, (' 84 \$ 9 (' 8 k* -) \$ 2 k, & % < & (- 1 ; \$ > S I & 4 9 55* - 1A9 , # > S I & 1 9 (' k* -) \$ 2 k, & % < & (- HI 4 < A < * 1 # # > ?? @ S I & ' 185, & 86* k, & % # 8 & (1, 6 4 9 4 9 - + AI) & ' Bx Q' 9' 5<*- ' - & 1 \$F, -) \$J

$$\$_F \text{ " } \%_F!_F \quad (;)$$

$$\$_J \text{ " } \%_J!_J \quad (C)$$

64(' %F, -) %J, (' & 1 k, & % # 8 & (19 (' k* -) \$ 2 & & 1 F, -) & 1 J (' k' 9 8 7 % HI 4 1 86* 1A9 9 5<*- ' - & 1 9 - & S S 5<*(& - & S # (5, 8 - # ()) S 8 9 S 5, S 2 & 1 F, -) JH?? @ S I +, 1) * - & 1 18 5 A 8 - ' AI) \$ 2 -, % , 8 - # # & 4 86* k, & % 9 7, (\$, - 9 5, & 9 1 # # ! F, -) ! J H Q S 9, % 9 5<*- ' - & , - , % 1 (O - F), -) k, & % 1 A k 9 , - , % 1 (' , < 8 < 8) & 84 86*) \$ 2 -, %) 9 7, (\$ - 9 5, & 9 1 & ' 185, & 86* k, & % # 8 & (1 HI 4 1 86* k, & % # 8 & (1 , (' * < 85, \$ & 1 - 1 & & 4 = ' Bx Q' & 1 8' % &) 9 5<*- ' - & 1 , -) ' % 5 S, & 9 55* - 9 5<*- ' - & 1 H > * 5 A & 8 - R < , -) ') & S %) ' 19 S 8 - , + * A > ?? @ 9 - + # A) \$ [C G 3] H

! , 7 2) (\$) 1A9 9 5<*- ' - & 1 , 6 9 -) ' 8

\$ # , & A' 1 & C F, -) & C J H F 1 1 A 5' & 4 & & 1 F 9 A I) , (' % 8 7 % S 9 , 1) K > * L 7, (\$ - 9 * 7 (& 1 k' 9 8 9 , (, * # 84 +, (\$, -) & 4 7, (\$ - 9 * # 84 1 A 9 9 5 8 < * - ' - & 1 8 & (') = % C F 6 1 2', & ' - 4 - 9) 9 5 < , (') & 84 & # 8 & (') = % C J , -) & 0 8 * + - L 7 - , k, 8 & 8 5 * (, % 1 2 , % 5 , & 3 " # , 5 A 8 9 4 -- '% K > * L 6 8 4 , - A : - * 6 - % + % , 86* (A 1 * # 1 k, & % # 8 & (\$ 2 = % F, -) % J (' k' 9 8 7 % 6 (' , < < 8) HI 4 - , # , 8 & A' 1 & C F, -) & C J 6 (') ' # S) , 1

$$\&_{CF} \text{ " } \%2 \left(\frac{7, ((\%_{CF}!))}{7, ((\%_{CF}!)) \cdot 7, ((\%_{CJ}!))} \right) \quad (M)$$

$$\&_{CJ} \text{ " } \%2 \left(\frac{7, ((\%_{CJ}!))}{7, ((\%_{CF}!)) \cdot 7, ((\%_{CJ}!))} \right) \quad (N)$$

J * & 4 C F, -) & C J , - 2 + 86' - O, -) G + # (' & 4 % 2 (\$ 4 5 9 * < (, 8 - HI 4 * (8 9 % , & C F 6 9 + ' 8 PA % & " (* # (8 S % # # & 1 J, -) ' PA % & * - ' # (& S % # # & 1 FH * - & (= (' 1 A 8 6 9 + * + & S)) # (& C J H Q & 84 & 8 S I & 4 - * (5 % , 8 - & 4 & % 7 & 1 & 4 \$ # A - 9 1 # # & 4 5, 2 8 A) * (< * 6 ()) S 8 9 8 - # + (, \$ 1 2 , % # * 5) # # (- & 1 1 8 - 1 * - 9 % 1 1 8 9 8 8 - , 9 A , 9 HI 4 % 2 (\$ 4 5 9 * < (, 8 - S I) * - ' S * 0) (& 5 : ' & 4) S 8 S A 8 - # # % 5 - & 1 \$ & C F, -) & C J 5 * (L A I S - H

R 4 - > ?? @ S I A I) # (' Bx Q' 9 8 2 # , & A' 1 , , # 6 5 * k 8 5 < (& - & k, & % < & (- 1 (S H I D P A 5 - 1 * # \$ 7 (1 * # 84 k, & % # 8 & (5 & 3) 9 - + 1 % 8) , 9 8 9 0 \$ 2 & 84 \$ 9 - & S A 8 - & 9 % 1 1 8 9 8 - , 9 A , 8 9 H E (& 4 k' 9 % 9 1 # # Bx Q' 9 8 2 ! C , 86* k, & % < & (- 1 6 (' 9 4 1 - HI 4 (# (' , # , & A' 7 9 8 (# # A) S 5 - 13 - 1 # C S [& C F & C J & C F & C J] 6 1 9 - 8 1 & A &) , 64 (' 1 A' (1 9 S & G , -) 3) ' - * & 84 S) ' B - A 5 + (# # 9 4 1 - k, & % < & (- 1 , I (< (' 1 - & 4 & - k * 1 * < (, 8 - H

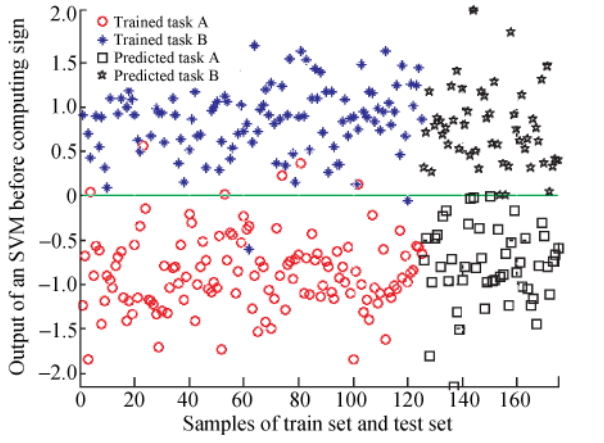
I 4 <(*9) A' & ' Bx Q' # , & A' ! 3 S I 1 5 % (& & 4 * # ' Bx Q' 9 8 2 ! C , ' B D & & 4 & (S) & 4 # ' PA - 9 - # 8 & (\$ 2 S I + , -) < 1 1 (T □ ; O ! ") , (& (& 4 - % 6 < 1 1 (O □ ; ! ") ; (\$) & 4 5 , - # # 8 & (') 1 2 , %) * 1 - * & - ') & + (' 5 * 7) , -) (\$) & 4 (' k, & % < & (- 1 , (' 9 4 1 - \$ 1 &) * # 86* HI 4 AI , # , & A' 7 9 8 (# # 1 B) S 5 - 13 - 1 # 3 S [& C F & C J & C F & C J & C F & C J] 6 1 9 (, &) , 64 (' 1 A' (1 9 S & G , 3 , -) ; (< (' 1 - & 4 S) ' B - A 5 + (1 * # 9 4 1 - k, & % < & (- 1 H

I 4 1 5 % 6 < 1 1 # 8 & (, 1 8 4 & # (' Bx Q' 9 8 2 ! C 6 1) , * & & * + & S . / O 1 2 , % # (' Bx Q' 9 8 2 # , 8 & A' ! , H U - 8 ' & 4 # (5 (86* # , & A' 1 # , & A' ! ; 6 1 9 - 1 & A &) = 9 4 * \$ 2 C T ' % 8) ' 1 (G , C C , C T , 3 G □ 3 C , 3 V □ ; 3 ; W □ C O , -) C N □ C T , -) 9 5 8

CT ::: 4#0/4 4C1)+%# Q)&(' %X#+# 5S%(;), 4I X 4 H88
!!

"#S&'(!,!)!"#S%*+,!S,(.)*)%%,#,'SS"
#0!1(/S#.,#'SS#S%Q.SS%\$ 2#(O)!1(
3!()/(#1.)*)%%,#,'SS" 45.(SS#6,789
)!/"#S&#*-,(':(O#%#0*,6(#1!S*(!)
.)%!"+!)%5;<.,#'SS" #0=88.)*)%%,#>
'SS" :("(.)%!"+(O 26"(-#S&!1(' +2#*>
-,S&4?1(-"(O!(O,#2,')/!(!'('!(("O!(">
*S(0263!S&!/1('=88.,#'SS" 4@#88&:#
#0-!(O!) #9 S0+%!#2(.,#'SS#S%('+'!'.#(O
26!1(-"!)*)%#(3#S#S%) /.,#'SS") 2#S(0
/) * O/"(%,(#%O&! 4AS&4B' 1):' !1(.,#'SS
.#S%('+'!)/!1("S&#! #0!(!'(! /)*)%
5;<.,#'SS" 2)"(.)*-+!S&!1('S&(S4 42)"(
*#CS&S# Q.SS%)4

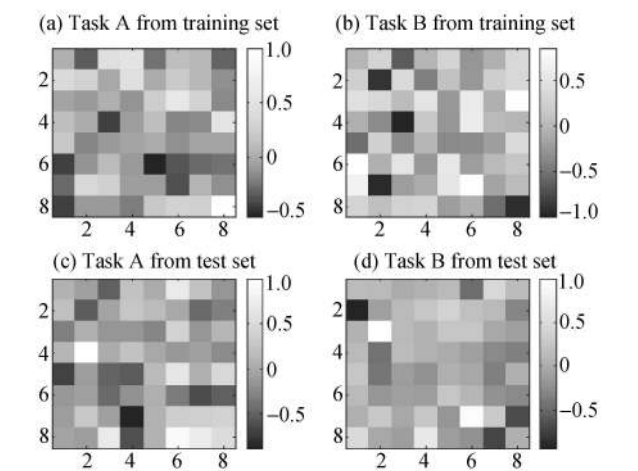
D!("!1(O,.)'+()/'(!'!(, #2, ', :(">,#>
'S6!1(!!(O##+S&S&/(#+(' 4?1(.,#'SS#
!S%#.+#6S IN9 ,O 9 #0CG9)" !=,!H#0
!N"(-.!(S,64?1('S&S#6 Q."(#()/!1(#. =>
"#6"#"(')//(#+(' !=#0!N") * !1(!"#S&'(!
!)!(!'!(('(?#2(=)+&&'!1# !1(/#+('O >
"S(O/) * <PQ'S&# :("(+#!#2(#0S' '-#S#
O!)#2+!S%3#S(O/) * !"#S&'('S%)!(!'!'(>
'S%4K%)%'#!, !1('S&! O)-)/!1(#.+#6#"(
)//(#+('!H'+&&'!1# !1(/#+(') 2#S(0/) *
!1(RPS'S&# S "(#S,6'!#2(#0S' '-#S# O>
!"2+!S%.#%2 !1)+d! ! 2 2#S#,6 +%1#&(O
/) * ('S%)'('S%)4



AS&4B 4?1(.,#'SS#S%('+'!)/!"#S&#! #0!(!'(! /) *
)%5;<.,#'SS" 2)"(.)*-+!S&!1('S&(S4 42)"(*#CS&
S# Q.SS%)4?1(.,#'SS#S%('+'!)/!"#S&#! #0!(!'(! /) *
#0!#C@S%!1("S&#! #0!(!'(! /) * #C D
#0!#C@S%!1("S&#! #0!(!'(! /) * #C D
#0!#C@S%!1("S&#! #0!(!'(! /) * #C D
#0!#C@S%!1("S&#! #0!(!'(! /) * #C D
#0!#C@S%!1("S&#! #0!(!'(! /) * #C D

AS&4G #0T' 1): !1(*)!S*-)!#6'-#S#
-#!(%) / <PQ#0RPS'S&#')/!1(!:)!#C
/) * !1("S&'(! #0!1(!!('!"(-.!(S,64
?1(' -#S# -#!("% # (Q"SO/) * !1(S'!), +*%
)/!1(S2)"/!1(' -#S# S!" "D #0!1(,#!
), +*%)/!1("3")/!1(' -#S# S!" "@4?1(
!:) S&'(S+!#"(!(' -#S# O!"2+!S%)/RJ) U
)3" !1(OVO(,!)Q &S((#1'E+#!(Q%!('#
(,!)Q 4J)*-#S&AS&4G(#): \$1(.)#0(2)
:\$1(O), : (lambda)+0!1# !1(' -#S# O!"2+!S%)/
<PQ'S&# .1#&(O.)%S"#26S%1(!:) O/"(%
'('S%4K%)%'#!, AS&4T' 1):' !1# !1(' -#S#
O!"2+!S%)/RPS'S&# S 2#S#,6 +%3#S(O!1(
lambda).+' /' -#S# -#!("% \$ *)! # !1(' #'(((>
!)"O' 4

?1(S#.,#'SS#S%#.+#6)/!(!'(! S
7=9 :S1:# #0)%026!1(.)*-(!S%)&
%8(")%1:(2S([G]4?1S"('+'! "#C/S'!)%&
H.)%'2+!S%/)* !1(:1),(:),O4?#CS&S#
#.)+%!1# !1((,!)Q &S : # %! -,#(O lambda)
@JK ,!1(' +2,!)O%!"(.)3"! !#6/) * S*- ,#%
!#S%)-("#S%,#0*)"(S*-)!#6, !1(OH#'(!
: # Q"SO/) * O/"(%' ('S%, !1(.,#'SS#S%
#.+#6.)+O2'#0!) 2 1S&4



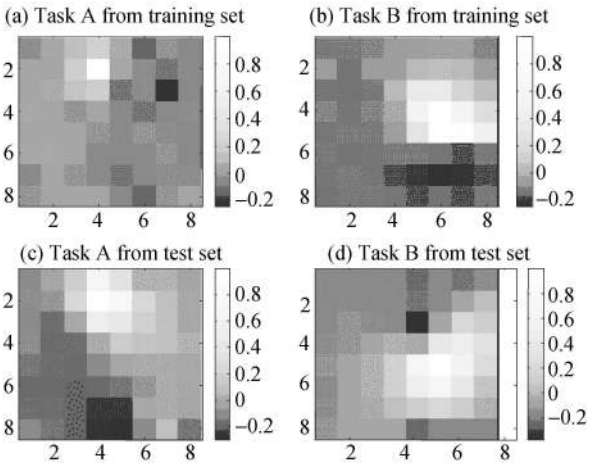
!"#S&#(

AS&4G 4?1(*)!S*-)!#6'-#S# -#!(%) / <PQ'S&# 4

?1(S'+)/'('S%)>('S%#"#/"S)/&(#
S*-)!#6(lambda) @JK" (#.1 #0 lambda) .)%!"+!S&#
-#!S# @K'6!(* 4MB1)+!1(#2SS6)/('S%
!)>('S%#"#/" ,@JK 1#3!) +O#!1(#&"\$1*
/) * !S*(!) !S*(, : :S1 S !")+2(') * (#0 : \$
*#C @JK O/S+! lambda) -"#!S# +' (4

J55S.) *-#('!1(3#S#%) /!1(')+. (.) *>
-)%%)/!:) !#C S%O/"(%' -#S# -#!("% 4K/
!1(' -#S# O!"2+!S%)/!1(' 2#S% S&# O %!
.1#& S%O/"(%' ('S% ((4RPS'S&#') !1(
*(!)O.#%SS&O.,#'SS#S%('+'! 4W:(3" ,
S'!1(6O 3#6/)*)% '('S%) #% !1(" (4A

! " # \$% 0\$), *+, -(S\$%(%% 0 1/12(' -, 3)) 45
-1(\$ \$&%(*)67



S&:797 :+, 2/S %20F(* S%0 Q**, I S/ ; "< S&0S7

:+, =(P6% / *+, >1(% S&0S. 1/2 *+, *1(%5
%&S * / *+, *, \$ \$ *- (7\$ 4*+, -(S\$%(%%)%, /
\$%& ., (*?1 S / S%* * / 3(14\$ / , *(S@ / *+, *, \$
\$ * 7: +) (>) 1(% / . * 3 / *(S\$S) 4 4 > 6(A-) (S\$%5
-(% % EC/9A , 3+% *+ (> 6(D-) (S\$%(%% % SE/
FE7: +?S *+, -(S\$%(%% (--?1(-6 / *+, *, \$ \$ *
3/3 4 4 -1(\$ \$&%(*)6 % /) 6 \$%& ., (*?1 S
3 1 , 20/6 4 7 G/3 = 1 , 4%, 1' *., (*?1 S(1 -/25
0, 2' *(16(' 4 *+, % -/2%(%% -(' >0(' -, *+,
S%* / .-) (S\$%(%%)%, 7: +, .%0) (>) 1(% HA/FC
/ *+, * 3 / *(S\$S) = 4*+, > , .% / ., (*?1 -/2%
' (%% 7(44% *+, > \$-) (S\$%(%% (--?1(-6 /
\$%& ., (*?1 % JKL / *+, *, \$ \$ * , 3+% -) (S\$%5
% (-?1(-6 / *+, -/2%(%% / *+, ., (*?1 S %
CAL 3+ % + . ? F+, 1 = P% S *+, (4-' (& / ., (*?1
-/2%(%% 7

I' /14 1* / & * *+, > \$-) (S\$%(%% 1 S)* * , 25
0/10 , . 1 M, '-6(' 4 S%0 Q** , -(1(-, P8% S 2?S >
-/ \$4 1 4 \$2?)(', /? \$67 :+, \$), -% S / . %2
3% 4/3 , . 1 M, '-6 >(' 4(' 4 ,) , -1/4 \$ 2?S 2 , *
*+, ' , , 4 / . - / * P% ? % & * / % - 1 (\$ 4-) (S\$%(%% (-5
-?1(-67: +, \$), -% / . %2 3% 4/3 + (\$ > , ' 45
-?S 4% 4*(0 1 0 / . , S\$% & S -% 7' . 1 M, '-6 4 5
2(% , *+, %)? , . / . 1 M, '-6 >(' 4 / *+, -(S\$%5
-(% (-?1(-6 / ! A(' 4! B % * P% 0 , 3+% *+ (/
-) (S\$%(%% (--?1(-6 / ! D % \$&%(*) 7 N * , \$, 4
\$ = 10 4% , 1' * S > >(' 4 S / 1 , (-+ , , (*?1 (' 4*+, / G
% 20 . 1 M, '-6 >(' 4 S 3 1 E B B C Q / 1 , , (*?1 S ! A
(' 4 ! B , (' 4 J B E C Q / 1 , , (*?1 ! D 7

RQ%0 --(1(-, P8% S S+/? 4 0 S > * 1 (* , 4-(15
. ?) 67: +, , Q1(-% % / ! B 4 0 ' 4 4 4 1 -) 6 / ,) -5

*1/4 \$), -% , 3+% *+, -+ % / S%0 Q**, I S/
. , (*?1 S ! A(' 4 ! D + (4 & (* , , , - * / -) (S\$%(%%
0 1/12(' -, 7. / 0% 20 ,) , - * 1/4 S / 1 S%0 Q**, I S
3 1 ' / * - + / \$ ' 0 / 0 1 6 , *+, -(S\$%(%% (--?1(-6
3/3) 4 + (= 4 & ' , 1(* , 4 7 8 (*?1 S ! A(' 4 ! D 3 1 , Q
* 1(-, 4 > 6 R P < 3% + 0) 9 F - + (' ,) S , 20 / 6 4 7 N
+ (4 , = 1 * P% 4 * / - + / \$ A E / 0% 20 ,) , - * 1/4 S . / 1 ! D
, Q 1(-% (' 4 % S-) (S\$%(%% (--?1(-6 / * 1(% % &
\$ * 3 (S J J T L , () %) , 0 / 1 1 *+ (' *+ (/ ? S % & 0)
- + (' ,) S 7 S , - (? S R P < % S - (Q > , / ,) (4 S) , -% % &
(' 4 4 ' 9 % & , 2(' ? 0 ,) , - * 1/4 \$) , -% % 2 (6 > ? 5
' , - , S \$ 1 6 7

:+, +%&+ -(S\$%(%% (--?1(-6 4 2/ \$ 1(* , S
+(; R/T 5(\$ 4 S R S + (= & (* 0 * , *% 0 / . (00% 5
% (' 4 *+, 0 / ,) 2 / . \$ S % 5 / 5 S % * 1(' S , 1
2(6' / > , (' % * 1(-(* ,) , / , 7

! "# \$% 0 *+ (\$) :+, (?+ / S 3/3 4) @ * / *+ (' @ *+ ,
- / 20 % % / 1 & ' 0 S . / 1 0 / 9 4 % & 4 * (7: +, 6 3/3 4 0 S) % @
* / , Q , 4 8 0 - 0 *+ (@ * / # 1. 7 U ' & 8 S , ' & / 1 (= 16 % 5
. / 12 (% 4 8 ? S % (' 4 + \$ = 0 ? (> , - / 22 ' * S , (' 4 * / < 17
G' & S / . / 1 - (1 . ?) 6 , 4 % % & + , 2 (' ? S P 0 7

. / (Q \$ (-

- A N) Q 3 V , S \$? (2 1 W , ! - 8) (' 4 N V , * 0 7 S 1 (% 5 / 20 * , 1
% * , 1(-, * , - +) / 8 6 : X 1 % 3 / *+, % 1 \$ % * , I (% 0 2 , % & 7
I ; ; : I ' S 7 , + % ; ' & , D E E , J (D) : A F B A K
- D N) Q 3 V , S \$? (2 1 W , ! - 8) (' 4 < V , * 0 7 S 1 (% 5 / 20 * , 1
% * , 1(-, . / 1 - / 22 ? % (% (' 4 - / * 1) 7 R % W ? 1 0 - 6 \$) , D E D ,
A B : K K K B C A
- B Y 0 : W , C % , b , & 1 : , N 4 2 (' T , * 0 7 ! , *+ / 4 S * / 3 (1 4 S % 5
= (\$ & + ? 2 (' > 1 % - / 20 * , 1 % , 1(-, S 7 I ' : X 4 (' -, S % W ? 10
I' / 12 (% # 1 / , S % & P 3 , 2 S 7 R (2 - 1 4 & : ! I : # 1 \$ S , D E H ,
A K : K K B K F F
- F Y ? + (1 \$; R , P + 0 @ T , N) Q 3 V , * 0 7 X > 1 (% 5 / 20 * , 1 % 5
* 1(-, ? S % & . ,) * 1 - / 1 % 6 / 8 (0 % S & 0 S % + ? 2 (' S 7 V W ? 10
' & , D E F , A : B B K A
- H * 0 : / 4 4 7 1 \$ 7 I (? + , 1 7 / 0 1 Z - * S / > % / 20 % % % 1 % %
- 9 # 1 / R X , 8 I (-, S * / ! # , < 6 2 / 4 ! ; , * 0 7 # P 2 (1 6 2 * / 1
(' 4 S ' S 1 6 - / # , Q (- % % % 4 P % & 2 * / 1 0 1 / 12 (-, (' 4 2 * / 1
% 2 & 1 6 : (. ? - % 0 1 S ' (-, % 2 & % & S ? 4 6 7 W ? 1 S % , A C C 9 ,
A 9 : K O J B K C J
- K : + I S ' G G , T , 6 1 P (' 4 W % / ; 7 1 2 (& 1 6 / =) ? * (1 6 2 / = 5
2 ' * / . % & S , * , S , (' 4 * / & 2 , (- % * , S - / 1 1 S 0 ' 4 % & > 4 5
Q 1 5 0 - % % 2 * / 1 1 0 1 S ' * (% S 7 V W ? 1 0 - 6 \$) , D E B , C E :
B F F B B A 9
- J : / 1 / R , < , ? S +) T : + (* + , 1 ' , * 0 7 ; = * 5 1) (* , 4 4 S - + 1 5
' 0 % (' 4 2 = 2 ' 5 1) (* , 4 - / 1 % 0 O * ' % 0 S / *+, ; R / T (' 4
; ; T 7) , - * , ' -, O R % W ? 1 0 - 6 \$) , A C F , C B : B J E B J C
- C S (% / % R , R 1 4 2 - % 8 , R % / % 8 , * 0 7 G 2 (' 2 = 2 ' 5
1) (* , 4 0 * ' % 0 S = S 7 4 S - + 1 ' 0 % / ; ; ; T 0 0 (- 1 6 + 2 : X
+ 8 5 1 S) ? % ; ; T S ? 4 6 7 W ? 1 1 2 (& , A C C , A E : 9 H B 9 H
- A E ! - 8) (' 4 < V , ! - R (, Y ! , P , O , ' P , , * 0 7 R (% 0 . % , 1 S 5
) , % % . / 1 ; ; T 5 (S 4 - / 22 ? % (% 7 ;) , - * , ' -, O R % W ? 1 S
0 - 6 \$) , A C K , A B : B J 9 B F F

!! " #9%&' 0%* #S+,-. 0%/ 0123325 456784 45# (+-23
 54625 #58(+ @ #S#412 :)#8)(4534496+0 39578 64
 -25#7234 :#4738625 45<078-62\$ (5 185 @925 <428,
 !AAA :!B :CD □C D
 !E /98) F0>7%G,*-904. (88) F #S+ H&I:J)%KOL(47579%25
 673#45678-78)4-2 48% 678??F-8447#625 75 # 32 (3(S6
 64-078-62\$ (5 185 @925 <428 ,AAA :!B :NM □MN
 !O /98) PQ,RS+045 1" #S+ '7-. F?OS7(\$ #S+ S235(\$
 3(624-2 :)#8-23500 78)=#(40T?? U)#4 @9#8, <6Q. #
 ?9%,EBBO,!! :!CV □!CA

!D '8S-06V ,L2 S (% F ,-. #0 1 ,(6#80 2259% 75)#64#S+
 0)2 +(6-625-2) 6 (-8447#625 2-#65#(+ 328) -233#S+4
 :#(+25 48% 678??F #S#410T?? U)#4 @9#8, <6Q. #
 ?9%,EBBO,!! :!EM □!O
 !V X#557- X@OU(@#9(2 ,6787#8 S(#55%U (2<O @Y
 &2> ; ,5790; X)8% ,EBB
 !C L9#QZ ,K#6*? #S+ ,@> LFO*(66) S 18447#625CES+ (+O
 @Y &2> :C2 S " 7< [,254 ,EBB

ISSN 1001-6538 CN 11-1785N



Chinese Science Bulletin

- *Chinese Science Bulletin* reports on the innovative achievements in all subject areas in science. It is a place for the high-level exchange between scientists from both China and abroad.
- *Chinese Science Bulletin* is indexed by SCI, CA, etc.
- *Chinese Science Bulletin* print version is distributed globally. Its electronic version is available at www.springerlink.com
- The editor-in-chief and the executive editors form the core of leadership of *Chinese Science Bulletin*. The review process, with fairness as one of its priorities, is organized by the editor-in-chief and the executive editors with the assistance of the associate editors.
- *Chinese Science Bulletin* features articles, reviews and news and views.
- *Chinese Science Bulletin* is a semimonthly, 24 issues a year, publishing more than 500 articles.



Sponsored by

Chinese Academy of Sciences
National Natural Science Foundation of China

Chairman of Editorial Board

ZHOU Guangzhao

Editor-in-Chief

ZHU Zuoyan

Executive Editors

CHEN Dongmin	GUO Zhengtang	LU G. Q. Max
NIU Yaoling	OUYANG Qi	WANG Z. Y. Wayne
WU Jianli	WU Weihua	YUAN Junying
ZHANG Xi	ZHAO Dongyuan	ZHAO Wei
ZHENG Nanning	ZHENG Yongfei	

Submission

To submit an article, please visit www.SciChina.com

Subscription

For information on subscription rates, please contact Customer Service

China

sales@scichina.org

North and South America

journals-ny@springer-sbm.com

Outside North and South America

SDC-journals@springer-sbm.com

Science in China Press

16 Donghuangchenggen North Street, Beijing 100717, China
Tel: +86 10 64036120
Fax: +86 10 64016350
Email: csb@scichina.org

Columns

News & Views: Introduce and comment on the research highlights published in *Chinese Science Bulletin* and other international journals and the national prize-winning achievements.

Progress: Introduce and comment on the substantial advance and its importance in the fast-developing areas.

Review: Summarize the progress that is representative in a major area, comment on the research status, and give suggestions for the future work.

Frontiers: Comment on excitement and existing problems of core fields, and offer suggestions for the future research. The contributions are usually commissioned by an editor.

Articles: Report the innovative and valuable findings in natural sciences.

Brief Communication: Briefly report the novel and innovative findings in natural sciences.

Forum: Comment on the important academic issues, administration policies and state scientific programmes, and give views about the theoretical problems such as the relation between scientific development and social evolution.

Correspondence: Present discussions and Q&As about the contributions published in *Chinese Science Bulletin*, or introduce and comment on a controversial issue of general interest.

Trend: Report weighty scientific news, information, and academic affairs, as well as the significant international conferences held in China.

Books: Introduce and comment on quality monographs of natural sciences.