Legibili   of Chinese charac ers in peripheral   ision and he op-do   n in   ences on cro   ding

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A R T I C L E   I N F O

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A B S T R A C T

Wri   en Chinese is dis inc from alphabe ic lang ages beca se of i s enormo s n mber of charac ers   i h a grea range of spa ial comple i ies (s roke n mbers). In his s   d   e in es iga ed he impac of spa ial comple i   on legibili   of Chinese charac ers as   ell as associa ed cro   ding in peripheral   ision. O r res l s sho   ed ha for isola ed charac ers, hreshold si es of comple   charac ers increased fas er   i h re inal eccen rici   han did hose of simple charac ers, s gges ing possible " i hin-charac er cro   ding among par s of comple   Chinese charac ers. Ho   e er, s ch " i hin-charac er cro   ding   as rendered negligible b   s rong "be   een-charac er cro   ding in rod ced b   ankers. When he arge and ankers belonged o differen comple i   gro ps, he in ensi   and e en of cro   ding   ere grea l   red ced,   hich co ld be e plained b   op-do   n in   ences as   ell as lo   er-le el mechanisms. We s gges   ha cro   ding can be a rib   ed o m l iple mechanisms a differen le els of   is al processing.

1. Introduction

Mos s   dies of le   er legibili   se Roman le   ers. Roman le   ers are highl   s   lish is al s im li ha are made of a small n mber of s rokes, ha e no discernible par s, and are rela i el   niform in spa ial comple i   as a s im l s se . I is less clear ho   m ch of o r kno   ledge ob ained from s ch s im li can be applied o legibili   of Chinese charac ers (CCs) ha con ain 1   o as man   as 52 s rokes, and h s ha e a   ide range of spa ial comple i ies. Recen l   e repor ed a s   d   on legibili   of CCs in fo eal   ision (Zhang, Zhang, X e, Li , & Y , 2007), in   hich   e meas red hreshold (ac i   ) si es for si   gro ps of freq en l   sed CCs from lo   o high spa ial comple i ies, and de ermined he rela ionship be   een legibili   and op ical defoc s for Landol C, Snellen E and hree gro ps of CCs represen ing lo   , medi m, and high spa ial comple i ies. O r res l s sho   ed ha CC ac i   si es increase s eadil   i h s im l s comple i   , ho gh a   a slo   er ra e han   ha   o ld be e pec ed if   is al ac i   is based on discerning he nes de ails of he s im li. Moreo er, he ac i   si e s. op ical defoc s f nc ions of he hree CCs gro ps and Snellen E ha e similar slopes, differing onl   b   a   er ical shif (appro ima el   one,   o, and hree lines abo e E ac i   on an ac i   char , respec i el), s gges ing he feasibili   of   sing Snellen E ac i   ,   hich is he c rren s andard op o   pe for ac i   es ing in China, o deri e he legibili   of CCs in fo eal   ision. To   nders and he slo   er ra e of ac i   si e increase agains spa ial comple i   ,   e also de eloped a geome ric momen model, in   hich   e propose ha h man le   er recogni ion performance near he ac i   limi can be acco n ed for b   a se of global fea   res described b   eas - o- is ali e and percep   all   meaningf l lo   -order geome ric momen s (i.e., he ink area,   ariance, ske   ness, and k r osis; man -scrip   nder re ie   ).

The c rren s   d   e ends o r   ork o he legibili   of CCs, as   ell as cro   ding, in peripheral   ision. We are par ic larl   in eres ed in   o dis inc charac eris ics of CCs ha co ld affec peripheral charac er legibili   and cro   ding in   a s no normall   e iden   hen alphabe ic s im li are   sed. Firs , he majori   of CCs are spa iall   complica ed. Onl   4% of CCs are single-bod   charac ers (e.g., same sq are area as he single-bod   CCs. We s spec   ha in erac ions among hese par s co ld in erfere   i h recogni ion of a comple   CC as a   hole, and s ch in erac ions, or " i hin-charac er cro   ding, co ld be magni ed in he peripher . If his is indeed he case, ac i ies of differen comple i   CC gro ps ma   ha e differen spa ial scaling f nc ions in he peripher , and h s ma   no be deri ed from a s andard meas remen like E ac i   , as   e sho   ed pre io sl   for fo eal   ision (Zhang e al., 2007),   i ho proper compensa ions of scaling differences among CC gro ps. S ch a possibili o ld ha e impor an clinical implica ions in e al a ing peripheral ision of pa ien s ho read e ha con ain charac ers of differen spa ial comple i ies.

To address his iss e, in he rs par of he s d , e meas red hreshold si es of single CCs of ario s comple i ies a differen re inal eccen rici ies. B comparing he slopes of spa ial scaling f nc ions for differen comple i CCs gro ps, e re ealed an inferiori of comple CCs o simple CCs in he is al peripher , possibl indica ing " i hin-charac er cro ding among par s of comple CCs. We also meas red hreshold si es of anked CCs in a rigram con g ra ion o assess he impac of i hin-charac er cro ding on reg lar "be een-charac er cro ding.

The second dis inc charac eris ic of CCs e are par ic larl in eres ed in is ha , in real- orld Chinese e , more han of en is a charac er anked b charac ers of differen spa ial comple i- ies. S ch con g ra ions are rarel seen in alphabe ic lang ages beca se alphabe ic le ers end o ha e similar spa ial comple i- ies. In cases here he arge and anking charac ers ha e differen spa ial comple i ies, some basic s im l s proper ies, s ch as he brigh ness and he spa ial freq enc con en s, are differen be- een he arge and ankers. These and o her ph sical s im l s differences incl ding shape, si e, polari , e c., are kno n o affec cro ding b segrega ing he arge and ankers (Ch ng, Le i, & Legge, 2001; Hess, Dakin, & Kapoor, 2000; Kooi, Toe , Tripa h , & Le i, 1994; Na ir, 1992). Moreo er, a Chinese reader kno s na - rall ha he arge and anking charac ers i h er differen spa ial comple i ies in a rigram con g ra ion, s ch as 个需十, are dra n from differen s im l s gro ps, so ha he or she ill no repor a anking charac er as he arge . There is e idence ha s ch misrepor ing con rib es o cro ding (S rasb rger, 2005). Therefore, bo h s im l s differences and high-le el op-do n in ences ma affec cro ding hen he arge and anking charac ers differ in comple i .

In he second par of his s d e assessed he impac of arge anker comple i con ras on cro ding. We also designed e perimen s o isola e he op-do n in ence on cro ding, sing no onl CCs b also English Sloan le ers. Moreo er, af er isola ion of op-do n in ences, e ere able o manip la e s im l s ph sical fea res o iden if lo er-le el mechanisms nderl ing cro ding. On he basis of o r res l s, as ell as pre io sl repor ed ndings, e propose an eclec ic ie ha ses m l iple mechanisms a m l iple processing le els o e plain cro ding.

2. Methods

2.1. Ob e e, a d a a

Si obser ers i h normal or correc ed- o-normal ision par icipa ed in he s d . All obser ers ere o ng (mean age = 23.3 ears) na i e Chinese speakers i h college ed ca ion and a leas 6 ears of raining in reading and ri ing English. Obser ers ZJ and ZT ere coa hors and ere e perienced in ps choph sical e perimen s. The o hers ere ne o ps choph sical obser a ions and ere na are of he p rposes of he s d . Wri en informed consen as ob ained from all obser ers prior o he es s.

The s im li ere genera ed b a Ma lab-based WinVis program (Ne rome rics Ins i e, Oakland, CA) and ere presen ed on a 21-in. Son G520 color moni or (2048 pi el × 1536 pi el, 0.189 mm × 0.189 mm per pi el, 75 H frame ra e). The minimal and ma imal l minance of he moni or as 1.18 and 91 cd/m^2, respec i el . Vie ing as monoc lar in a diml li room. A head-and-chin res as sed o s abili e he head posi ion.

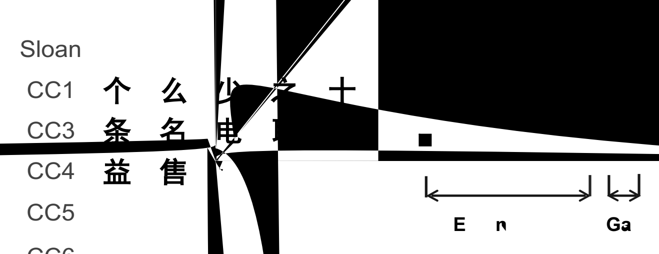
2.2. S

The es s im li (F a) onsis ed le ers and fo r gro f C s. Each le ers or charac ers (n e cep ion legibili as de ermi n a pre io ha s d , 500 mos q e l se gori ed in o si gr a ording (CC1 CC6 gro ps, fr 4 16 1 charac ers ere sele fr ach E clidean dis ances ar bi ial con g ra ion. T egi of en Sloan le ers, a eas a rigoro s ps choph l e s im li i h he s ib selec ed for he se i e per no sed). Since his le f a se charac er ac i , rec i ading, si CC gro ps of di n i ies, gro p names o be s o her ar ic he Sloan le ers a he same (50 × 50 pi els). The d niform s rok alen o 1/5 of he l n pe bold Hei as sed for CCs bec s had rela i el nif and ere free of ser n n mber of s rokes same area, s roke i be ad all hinner as he cha ers became more co . For 0 × 50 pi el bi maps e s d, er ical s roke id h f ed from predominan l 7 pi els i o predominan l 6 s in CC6, a ori on al s rok shif ed from 5 6 pi n CC1 o 4 CC6.

The spa ial comp of he s lso descri s roke freq enc (Z e al., 20 le er or charac er as sliced a 6 di n/posi ion bina i on al on he pper and lo er er ical on he lef and obliq el a 45° 1 cen ral por ion From each slicing e a erage crossed s ro c la ed he ma im f g as he s roke freq enc . The a erage s roke freq c an le ers as 2.0 s rokes/le er. The a erage s r fr for he si gro ps of CCs i creased mono onica fr 5.5 s rokes/charac er (Z e al., 2007).

2.3. P ced e

The arge as a lack er or Chines sen ed on a f ll-scre n f l ce hi e b ge as presen ed ei her a as anke aligned le ers or c arac m). T member of a s im s gr he



differen from each o her and from he arge . The ankers al a s had he same si e as he arge , and he edge- o-edge arge anker gap as one charac er ide if nspeci ed (Fig. 1b). The arge as presen ed a 0°, 5°, or 10° re inal eccen rici ies on he hori on-al meridian in he emporal is al eld. The ie ing dis ance as 6, 1.6, and 0.8 m for 0°, 5°, and 10° re inal eccen rici , respec i el .

In each rial of fo eal es ing, a 0.1° sq are a ion as rs displa ed for 200 ms a he cen er of he screen accompanied i h a beep, hich as follo ed b a 300 ms ime gap prior o he onse of he s im l s. The s im l s d ra ion as 200 ms. When ankers ere sed heir displa as al a s s nchroni ed i h he arge i h he same abr p onse and offse . For peripheral es ing, he cen ral a ion as al a s presen , and he obser er as asked o a e a i . A he beginning of each rial, a small sq are (0.1°) ashed for 200 ms a he arge loca ion as a loca ion c e, hich as follo ed b a 300 ms gap prior o he onse of he s im l s. The s im l s as presen ed for 200 ms. The obser er' ask as o iden if he arge from a lis of he e members of he arge gro p (he lis as prin ed on paper for obser er's reference), and o repor he res l b pressing a n mber ke . An a di or feedback as pro ided pon an incorrec response.

The hreshold le er si e i ho or i h ankers as meas red i h he me hod of cons an s im li. In E perimen s I and II, hich ere r n oge her, each e perimen al session as composed of hreshold si e meas remen s i h a combina ion of s im l s gro p, re inal eccen rici , and anking condi ions. Each hreshold meas remen as based on e le els of s im l s si e i h 10 presen a ions a each le el. A pical ro nd of e perimen s consis ed of 30 sessions (5 s im li gro ps × 3 eccen rici ies × 2 anking condi ions), hich ere r n according o a randoml perm ed able for each obser er and ere comple ed in abo o da s. Each obser er comple ed 7 ro nds of he e perimen s. All condi-ions in each s b-e perimen of E perimen s III and IV co ld be co ered i hin a 2-h session and ere repea ed in se eral da s. The percen correc da a ere i h a Weib ll f nc ion: $P = 1 - (1 - \gamma)e^{-(/)^{\beta}}$, here P as he percen correc , γ as he g essing ra e (0.2 in a 5AFC rial), as he s im l s ang lar si e, β as he slope of he ps chome ric f nc ion, and as he hreshold si e for recogni ion a a 70.6% correc le el.

3. Results

3.1. E e e I: Le b C e e c a ac e e e a

This e perimen meas red hreshold si es for fo r gro ps of isola ed CCs as ell as Sloan le ers a 0°, 5°, and 10° re inal eccen-rici ies. Indi id al and mean hreshold si es plo ed agains eccen rici , along i h regression lines (eigh ed i h error bars), ere sho n in Fig. 2a and b. A repea ed meas res ANOVA indica ed ha for all s im l s gro ps, he hreshold si es increased i h he re inal eccen rici linearl (< .001; Fig. 2a and b). The hreshold si es of he more comple CCs (CC4 and CC6) ere similar (= .978), and ere signi can l larger han hose of simpler CC1 (= .002) and CC3 (= .026). CC3 hreshold si es ere larger han ha of CC1 (= .032), and CC1 hreshold si es ere larger han ha of Sloan le ers (= .022). The la er co ld be e plained b he hicker s rokes of he Sloan le ers (Zhang e al., 2007).

There as a signi can in erac ion be een s im l s gro ps and eccen rici ies (< .001), s gges ing ha he increase of hreshold si es i h he re inal eccen rici as affec ed b he s im l s gro ps. To charac eri e his in erac ion, peripheral hreshold si es ere normali ed b corresponding fo eal hreshold si es. The res l an si e scaling f nc ions ere sho n in Fig. 2c, and he f nc ion slopes ere plo ed agains s roke freq enc in Fig. 2d. These plo s sho ed a s s ema ic increase of scaling f nc ion slope from simple o more comple CCs. The slopes of CC6 and CC4 ere 24% and 26% grea er han ha of CC3, respec i el , and 56% and 59% grea er han ha of CC1, respec i el . Moreo er, hen slopes of he scaling f nc ions for fo r CC gro ps ere plo ed agains he s im l s comple i ies (s roke freq encies), he slope of he regression line as signi can l differen from ero (= .002) (Fig. 2d). These da a indica ed ha he hreshold si es of more comple CCs (CC4 and CC6) increased a a fas er ra e i h he re inal eccen-rici han did hose of simpler CCs. We in erpre ed his s s ema ic change of regression slope as e idence for possible in erac ions among componen s of more comple CCs, or " i hin-charac er cro ding, in he is al peripher (see Sec ion 4).

3.2. E e e II: C d be ee C e e c a ac e

A le er is more dif c l o iden if hen i is closel anked b addi ional le ers (Flom, Hea h, & Takahashi, 1963; S ar & B rian, 1962. See Le i (2008) for a mos recen re ie). Wo ld s ch cro ding be een he arge and anker charac ers be affec ed b i hin- arge cro ding? In his e perimen e meas red he hreshold si es for anked Sloan, CC1, CC3, CC4, and CC6 arge s a 0°, 5°, and 10° re inal eccen rici ies. The arge and ankers ere dra n from he same 5-member s im l s gro p (Fig. 1a), and he edge- o-edge gap be een arge and ankers as al a s one charac er id h (Fig. 1b). This e perimen as r n oge her i h E perimen 1 on he same obser ers (see Sec ion 2). Indi id al da a, heir a erages, and he regression lines are sho n in Fig. 3a and b.

As e pec ed, s rong cro ding as e iden in recogni ion of anked Sloan le ers and CCs in peripheral ision. The slopes of spa ial scaling f nc ions ere m ch s eeper for anked arge s (Fig. 3c, dashed lines) han for isola ed arge s (Fig. 3c, solid lines, replo ed from Fig. 2c). In he fo ea, hreshold si es nder he anker and no- anker condi ions ere no signi can l differen (= .591), consis en i h Flom (1991) ha fo eal cro ding did no e end be ond one charac er id h.

The bes ing lines of he hreshold si e s. re inal eccen rici f nc ions became s eeper i h increasing CC comple i (Fig. 3a and b). Ho e er, his increase onl re ec ed fo eal hreshold si e differences among he CC gro ps. When peripheral hreshold si es ere normali ed b corresponding fo eal hreshold si es, he differences among he scaling f nc ion slopes of ario s CC gro ps ere insigni can (= .344; Fig. 3c). When he slopes of he scaling f nc ions for he fo r CC gro ps ere plo ed agains s roke freq encies, he slope of he regression line as no signi can l differen from ero (= .679) (Fig. 3d). These res l s s gges ed ha hen ankers ere presen , charac ers of differen spa ial comple i ies scaled in a similar manner i h re inal eccen rici .

I is impor an o dis ing ish he normali ed spa ial scaling fac-ors b fo eal hresholds in o r s d from Bo ma (1970) nnormali ed spa ial scaling fac ors. Bo ma (1970) repor ed ha he nnormali ed scaling fac or for cri ical cro ding one is appro ima el 0.5 (i.e., half he re inal eccen rici). This fac or aried from 0.23 (Sloan) o 0.37 (CC6) in o r da a hen he si es of he cri ical ones ere calc la ed in arge anker cen er- o-cen er dis ance a a 70.6% correc ra e (he hreshold al es ere in edge- o-edge gap si e in Fig. 3), smaller han Bo ma's fac or of 0.5. This difference co ld be d e o he differen cri erions se o de ne he hresholds (Le i, 2008).

3.3. E e e III: T e e ec a e a e c e c a c d

In he in rod c ion e s gges ed ha in normal Chinese e a charac er is more likel o ha e neighboring charac ers i h differen spa ial comple i ies. S ch comple i differences o ld

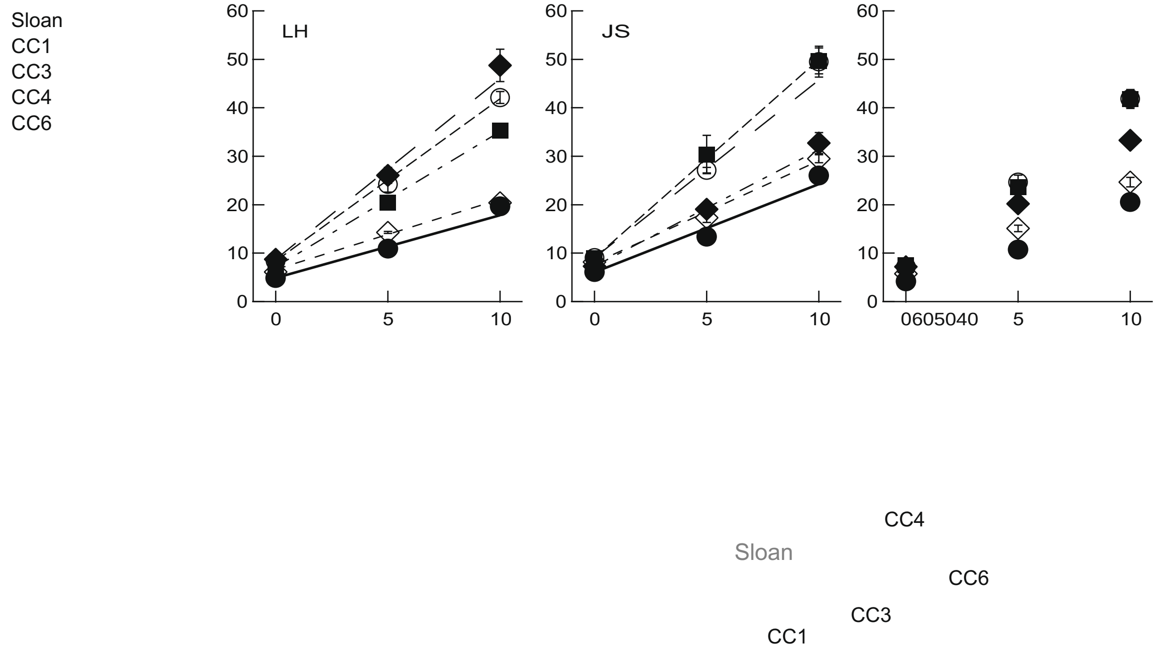


Fig. 3. Cro ding i h anked Sloan le ers and Chinese charac ers. (a and b) Indi id al and mean hreshold si es as a f nc ion of re inal eccen rici . (c) Scaling fac ors

introduce low-level brightness and spatial frequency differences between the target and flankers. It would also introduce a top-down influence to segregate the target and flankers, especially when the complexity difference is large. In this experiment, we measured the effects of target–flanker complexity contrast on crowding with CCs. Later in Experiment IV we would isolate the top-down influences on crowding using CCs as well as English Sloan letters as stimuli.

3.3.1. *The effect of target–flanker complexity contrast on crowding*

To maximize complexity contrast, the least and most complex CCs, CC1 and CC6, were used as target and flanker stimuli. The average stroke frequencies were 2.22 and 5.52 strokes per character for CC1 and CC6 stimuli, respectively. Threshold sizes were measured at 10° retinal eccentricity for CC1 and CC6 targets with three target–flanker complexity contrast conditions: (1) zero complexity contrast: a CC1 or CC6 target with flankers from the same 5-member stimulus group (denoted as "111" and "666" conditions. Digits "1" and "6" stand for CC1 and CC6 characters, respectively, and the left, center, and right digits represent the left flanker, center target, and right flanker, respectively); (2) full complexity contrast: a CC1 target with CC6 flankers ("616" condition) or a CC6 target with CC1 flankers ("161" condition); (3) mixed complexity contrast: a CC1 target with a CC6 flanker and a CC1 flanker ("611/116" conditions) or a CC6 target with a CC1 flanker and a CC6 flanker ("166/661" conditions). Threshold sizes for single CC1 and CC6 without flankers were also measured as baselines (denoted as "1" and "6").

Fig. 4 shows the threshold sizes obtained under various target–flanker complexity contrast conditions. When the target and flankers had full complexity contrasts (616 and 161), crowding was reduced significantly from that at zero complexity contrast (111 and 666) ($p = .001$, repeated measures ANOVA), by 55.5 ± 4.4% for the CC1 target (Fig. 4, gray bars) and 34.0 ± 4.2% for the CC6 target (Fig. 4, black bars). Crowding was reduced more for the CC1 target by the CC6 flankers in the 616 configuration than for the CC6 target by the CC1 flankers in the 161 configuration. This asymmetry could be due to the fact that for the 616 configuration, when the CC1 target was near threshold, the CC6 flankers were most likely below their non-flanker "6" baseline thresholds (Fig. 4). Therefore, the features of these CC6 flankers were no longer legible and had less chance to be improperly integrated with features of the CC1 target to produce crowding. However, crowding was not completely eliminated at full complexity contrast. Threshold sizes for 616 and 161 conditions were still significantly larger than "1" and "6" baselines ($p = .002$), which were 29.6 ± 4.0% and 38.7 ± 10.0% larger, respectively.

At mixed complexity contrasts, there was no significant difference whether the same-group flanker was on the left or right side of the target, so the results were averaged. Crowding at mixed complexity contrasts (116/611 and 166/661) was weaker than that at zero complexity contrasts (111 and 666) ($p = .008$ and .021, respectively, Fig. 4), but stronger than that at full complexity contrasts (616 and 161) ($p = .063$ and .021, respectively, Fig. 4).

However, it is worth mentioning that the above estimation of the complexity contrast effects were most conservative, with the assumption that the guessing rate of the center target was unchanged across various flanker conditions. However, letters at the beginning and end of a letter string are known to be more legible than letters in the middle (Wolford & Hollingsworth, 1974), so it was likely that at some character sizes in our experiments, the observers could recognize one or both flankers but not the target. When both flankers were recognized, the target guessing rate was 1/3 under zero complexity contrast conditions (111 and 666) because both flankers were member of the 5-character stimulus group, and 1/5 under full complexity contrast conditions (161 and 616) because both flankers were from a different stimulus group. The higher rates of correct guessing associated with the zero complexity contrasts would have caused underestimation of the threshold sizes for the 111 and 666 conditions, and underestimation of the threshold differences between the zero- and full-complexity contrast conditions.

3.3.2. *The effect of target–flanker complexity contrast on critical spacing*

Besides the threshold change, crowding is also quantified by its spatial extent or critical spacing (the zone within which flankers interfere with the target recognition). Several studies reported that

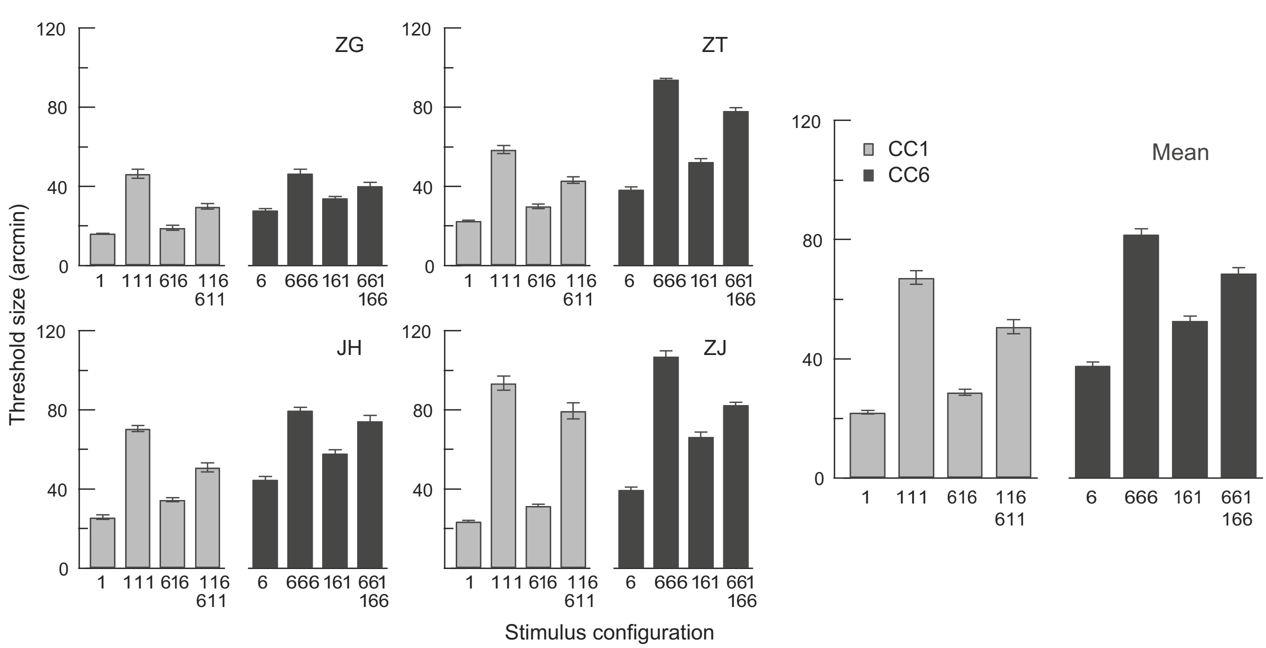


Fig. 4. The effects of target–flanker complexity contrast on crowding. 111 and 666: zero complexity contrasts; 616 and 161: full complexity contrasts; 116/611 and 661/166: mixed complexity contrasts. Digits "1" and "6" stand for CC1 and CC6 stimuli, respectively. The left, center, and right digits represent the left flanker, center target, and right flanker, respectively.

he cri ical spacing is appro ima el half he arge re inal eccenrici regardless of he arge si e (Bo ma, 1970; Ch ng e al., 2001; Pelli, Palomares, & Majaj, 2004; Tripa h & Ca anagh, 2002), b he e ac al e depends on ho he spacing is de ned (cen er- o-cen er or edge- o-edge) and ha he cri erion is o de ne he limi s of he cro ding one (Le i, 2008).

We meas red cri ical spacing of cro ding a ero comple i con ras s (111 and 666) and f ll comple i con ras s (616 and 161) a 5° and 10° re inal eccen rici ies for he same fo r obser ers. Cri ical spacing for Sloan le ers a ero comple i con ras as also meas red for comparison. The si es of he arge and ankers ere ed a 1.2 imes each obser er's single charac er hreshold si es (Fig. 4), and he arge correc repor ra e as meas red as a f nc ion of he arge anker cen er- o-cen er separa ion. Cri ical spacing as de ned as he cen er- o-cen er separa ion a a 70.6% correc ra e. Cri ical spacing for ero comple i con ras condi ions (111, 666 and SSS for Sloan le ers) as s a is icall similar a 1.80 ± 0.47°, 2.26 ± 0.49°, and 1.85 ± 0.47° a 5° eccenrici (Fig. 5a), respec i el , and a 3.17 ± 0.13°, 3.24 ± 0.44°, and 3.26 ± 0.17° a 10° eccen rici (Fig. 5b), respec i el (= .462, repea ed meas res ANOVA). Ho e er, cri ical spacing as signi can l smaller hen he arge and ankers ere a f ll comple i con ras s (= .006), i h an o erall red c ion of 41.0%. The 616 comple i con ras condi ion red ced more cro ding from he 111 condi ion (b 49.4%, a eraged o er 5° and 10° da a, Fig. 5a and b, gra bars) han did he 161 comple i conras condi ion from he 666 condi ion (b 32.6%, a eraged o er 5° and 10° da a, Fig. 5a and b, black bars) (= .006). The red c ions of cri ical spacing ere similar a 5° and 10° re inal eccen rici ies (= .161).

3.4. E e e IV: T -d a d e-e e e ce c d

S rasb rger (2005) repor ed ha nder cro ding an obser er migh repor he anking le ers as he arge , hich as s ppor ed b o r error anal sis sing he 111 and 666 da a in Fig. 4. Speci call , for all s im l s si es prod cing less han 60% correc arge repor ra e (mean = 38.6% and 37.8% for 111 and 666 condiions, respec i el), he ra e ha he obser ers mis akenl repor ed one of he o anking charac ers as he arge as signi can l higher han he ra e repor ing he o her o n sed charac ers (52.5% s. 8.9% for he 111 condi ion and 44.6% s. 17.6% for he 666 condi ion; < .001, repea ed meas res ANOVA). These misrepor ing ra es ere calc la ed agains he o al n mber of incl ded rials, no he n mber of rong repor rials, so he obser ers e en repor ed he ankers more freq en l han he correc arge . Ho e er, hen he arge and ankers ere dra n from differen s im l s gro ps (i.e., 161 and 616 condi ions), he obser er o ld no repor he ankers as he arge , beca se he or she kne ha he anking charac ers ere no on he lis of repor able charac ers. Besides s im l s differences (i.e., brigh ness, spa ial freq enc) ha migh ha e segrega ed he arge and ankers, ho m ch o ld his op-do n in ence con rib e o cro ding red c ion in Fig. 4? In his e perimen e a emp ed o isola e his op-do n in ence on cro ding, as ell as o s d lo er-le el mechanisms ha also affec cro ding.

3.4.1. H -e e -d e ce

To isola e high-le el op-do n in ences, e compared cro ding hen he arge and ankers ere dra n ei her from he same s im l s gro p, or from differen s im l s gro ps, hile keeping he arge anker comple i con ras cons an . To make his possible, as sho n in Fig. 6a, he arge in he rigram as al a s dra n from he e CC1 charac ers sed in abo e e perimen s, and he ankers ere ei her dra n from he remaining fo r charac ers ("same anker condi ion in Fig. 6), or from e o her charac ers ("diff anker condi ion in Fig. 6). These ne charac ers and he e is ing e charac ers had similar n mber of s rokes (2∼4) and similar bi map E clidian dis ances among each o her (Zhang e al., 2007). Therefore, he arge anker comple i con ras s ere ero nder "same and "diff anker condi ions, b he ankers in he "same condi ion ere repor able charac ers and he ankers in he "diff condi ions ere no . The obser ers ere clearl informed he her he arge and anking charac ers ere from he same s im l s gro p or from differen gro ps, and he s im li ere lis ed on paper as a response g ide. This design isola ed he obser er's kno ledge of arge and anker iden i ies as a op-do n in ence on cro ding and con rolled he impac s of lo er-le el s im l s fac ors. We also ran a parallel e perimen sing Sloan le ers follo ing he same proced re. The arge as dra n from e Sloan le ers (CDKNS) sed in abo e e perimen s, and he ankers ere dra n ei her from he remaining fo r le ers, or from e o her pre io sl n sed le ers (VROHZ, Fig. 6a).

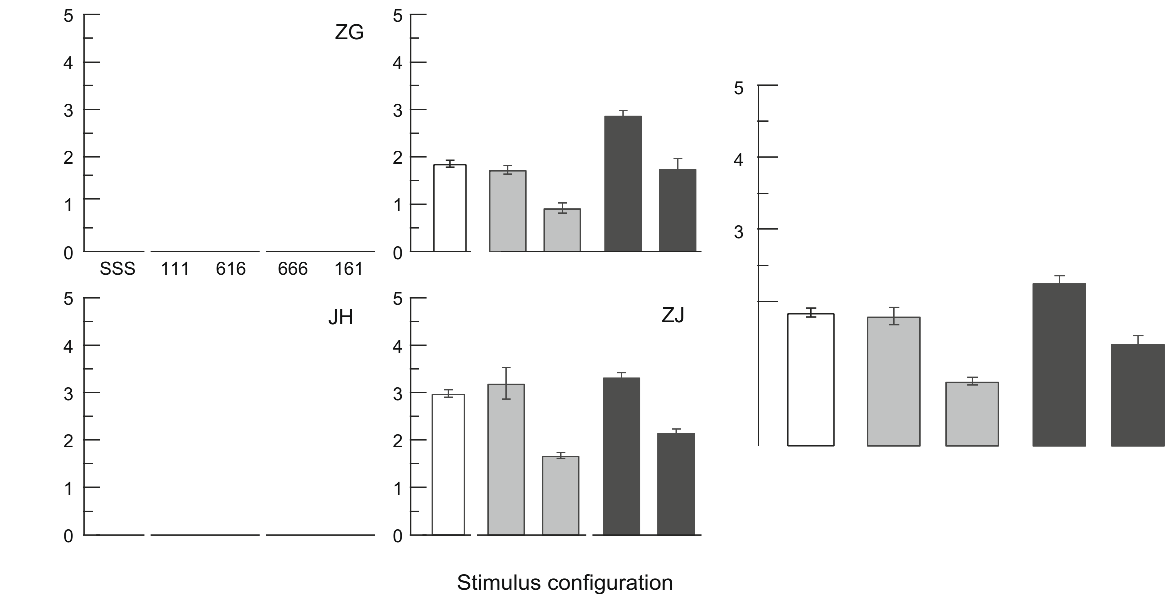
Fig. 6b sho ed ha hen he ankers ere dra n from a differen s im l s gro p, cro ding as signi can l red ced (= .007, repea ed meas res ANOVA). The mean hreshold si e as red ced b 27.9 ± 6.3% for CC1 and 19.5 ± 5.6% for Sloan le ers. There as no signi can difference of cro ding red c ion be een CC and Sloan le er s im li (= .221). These res l s demons ra ed ha he obser ers' kno ledge of arge and anker iden i ies as a op-do n in ence co ld signi can l red ce cro ding. Ho e er, compared o hreshold red c ion in he f ll comple i con ras condi ion (616) s. he ero comple i conras condi ion (111), hich as 55.5 ± 4.4% (Fig. 4), hreshold red c ion in he "diff anker condi ion s. he "same anker condi ion a he c rren ra e of 27.9 ± 6.3% as less rob s . This difference s gges ed ha op-do n in ences co ld onl acco n for par of he f ll comple i con ras effec on cro ding, and he remaining effec needed o be a rib ed o s im l s ph sical differences ha also segrega e he arge and ankers o red ce cro ding (Ch ng e al., 2001; Hess e al., 2000; Kooi e al., 1994; Na ir, 1992).

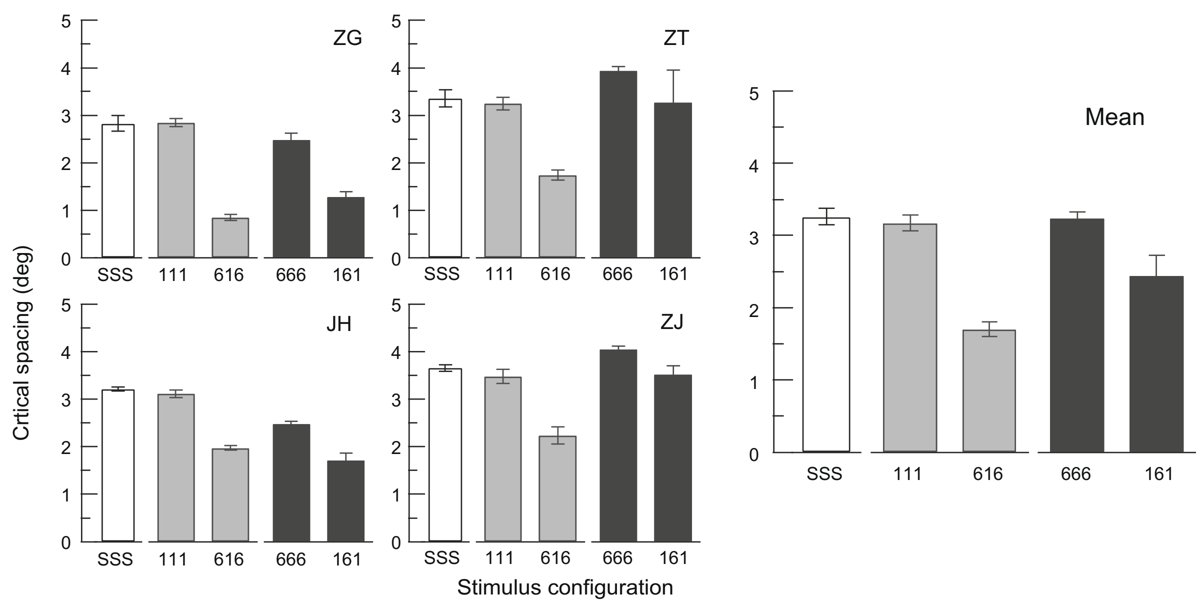
Again, he abo e calc la ions of hresholds implici l ass med eq al g essing ra es of he arge in "same and "diff anker condi ions. Under he condi ions here bo h ankers ere recogni able, he arge g essing ra es for he "same and "diff condi ion o ld be 1/3 and 1/5, respec i el . So he abo e es ima ion of he op-do n in ences on cro ding, hich as re ec ed b he hreshold differences be een he "same and "diff anker condi ions, as mos conser a i e, as disc ssed in E perimen III.

3.4.2. A c e e e ea e e a de c d

I has been proposed ha cro ding res l s from in ermedia e-le el improper in egra ion of arge and anker fea res hen he arge and ankers fall in o an in egra ion one (Le i, Hariharan, & Klein, 2002; Pelli e al., 2004). Ha ing q an i ed he op-do n in ences on cro ding, e ere able o manip la e lo er-le el anker proper ies o ha e a close look of his improper fea re in egra ion process. Speci call , e meas red cro ding i h s roke-scrambled CC1 ankers ("s rkS condi ion, Fig. 6), hich scrambled he spa ial arrangemen of he s rokes b re ained all legi ima e br sh s rokes (fea res), and i h pi el-scrambled CC1 ankers ("p lS condi ion, Fig. 6), hich abolished all legi ima e s rokes, and compared hreshold changes agains o her anker condi ions.

Like he "diff anker condi ions, obser ers o ld no repor he ankers as he arge b mis ake in he s roke- and pi elscrambled anker condi ions, so his op-do n in ence as ma ched. Moreo er, s roke-scrambling broke le er-le el processing of anking charac ers ha o ld ha e ied fea res oge her, possibl allo ing he s rokes o be more easil in egra ed in o





he arge . Mean hile, pi el-scrambling des ro ed fea res of he anking charac ers, h s disco raged arge anker fea re in e-gra ion. The res l s sho ed ha s roke-scrambled ankers (“s rkS) raised hreshold si es b 38.4 ± 7.6% compared o hose i h he nscrambled “diff ankers (Fig. 6b; < .001, paired - es), s gges ing ha le er-le el gro ping of anker fea res dis-co raged arge anker fea re in egra ion. Moreo er, af er his le er-le el fea re gro ping as disabled b s roke-scrambling of he ankers, he hreshold si es ere no signi can l differen from he “same anker condi ion le el (= .95). I is or h men-ioning ha al ho gh he “same and “s rkS ankers prod ced similar cro ding, cro ding b “s rkS ankers as affec ed b o co n erac ing processes: a op-do n in ence ha red ced cro ding, and a freer arge anker fea re in egra ion d e o dis-abled le er-le el fea re gro ping ha facili a ed cro ding. S ch d namics ere no discernible i ho a baseline reference of op-do n impac se b he “diff anker condi ion. On he o her hand, pi el-scrambled ankers (“p lS) nearl iped o cro d-ing. The hreshold si es ere no signi can l differen from he no- anker baselines (= .086). This effec as predic ed b he fea re in egra ion model, beca se af er pi el-scrambling, here ere no eligible fea res in he ankers ha co ld be in egra ed i h he arge o prod ce cro ding.

4. Discussion

In his s d e demons ra ed i hin-charac er cro ding in recogni ion of isola ed, predominan l comple , CCs in he is al peripher , and sho ed ha s ch i hin-charac er cro ding as rendered negligible b m ch s ronger be een-charac er cro ding once he arge charac er as anked b o her charac ers. We also fo nd red ced cro ding as a res l of spa ial comple i con ras

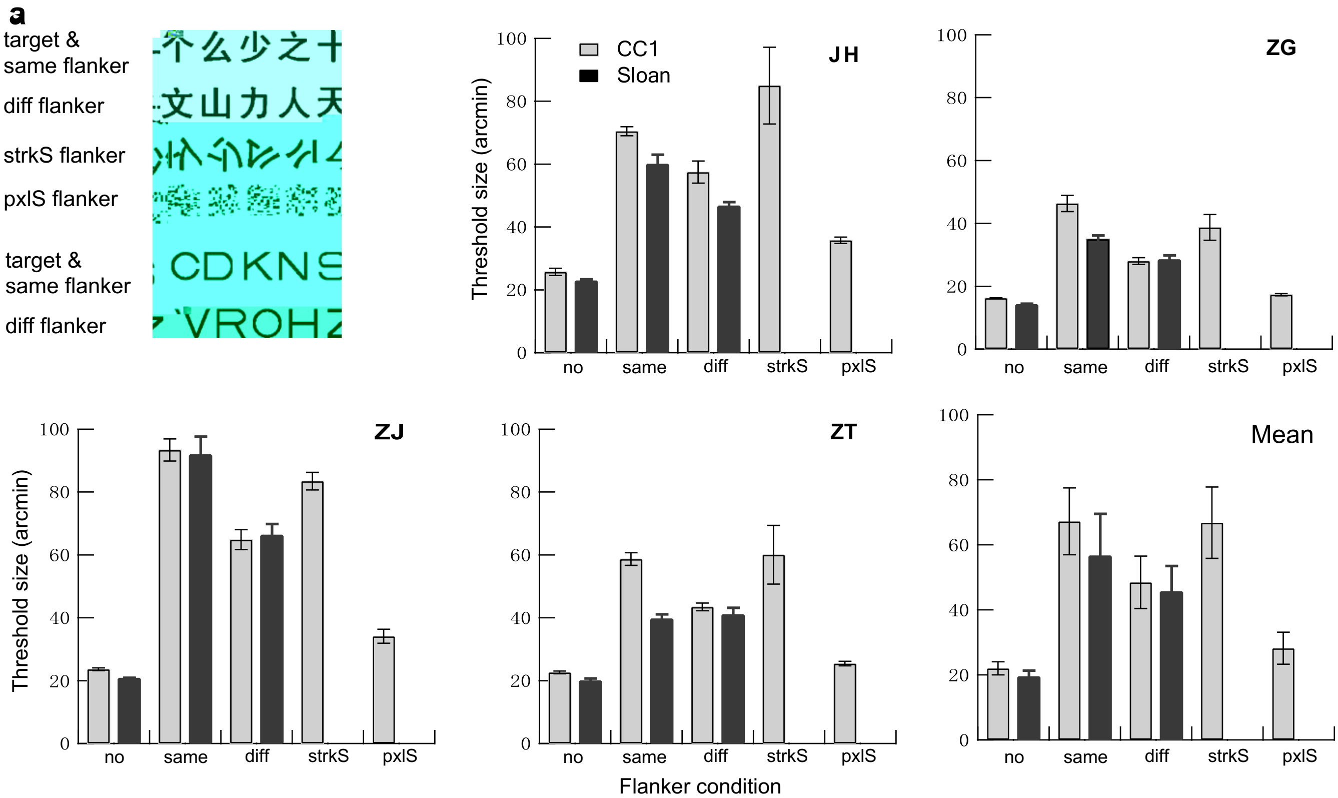


Fig. 6. Top-do n and lo er-le el in ences on cro ding. (a) CC1 and Sloan le ers sed as arge and differen anker s im li. (b) Threshold si es a differen anker condi ions. no: no- anker; same: he arge and ankers dra n from he same s im l s gro p; diff: he arge and ankers dra n from differen s im l s gro ps; s rkS: s roke-scrambled ankers; p lS: pi el-scrambled ankers.

be een he arge and anking CCs, and assessed he con rib - ions of op-do n and lo er-le el processes o his comple i con ras effec and o cro ding in general.

4.1. W -c a ac e c d a d c ca ca

O r da a sho ed ha , as he re inal eccen rici increases, comple CCs ha e o be enlarged a a more rapid ra e han simple CCs o reach eq al legibili . Comple charac ers ha e more s rokes han simple ones, and h s ha e higher objec spa ial freq enc componen s (c cles/char, Parish & Sperling, 1991). Wo ld he differences in objec spa ial freq enc acco n for spa ial scaling differences among differen CC gro ps?

I is kno n ha is al ac i aries linearl i h re inal eccen rici (Herse & Bedell, 1989; Le i, Klein, & Ai sebaomo, 1985; L digh, 1941; Ro amo & Virs , 1979). If S and S_E are c -off re inal freq encies in he fo ea and a E deg eccen rici , hen $S_E = S/(1+E/E_2)$, here E_2 is he eccen rici a hich he resol ion has changed b a fac or of 2. For a charac er hose heigh is H deg and hose objec freq enc is c/char, i s dominan re inal spa ial freq enc is $/H$ c/deg. When ac i hreshold heigh is reached a an eccen rici E, he charac er's re inal freq enc $S_E = /H = S/(1+E/E_2)$, and he hreshold charac er heigh sho ld ar i h eccen rici in a linear fashion: $H = (1+E/E_2)/S$. A he fo ea, he ac i heigh is $H_0 = /S$. If e normali e each c r e b i s o n fo- eal ac i heigh H_0, he normali ed ac i heigh ill be $H = H/H_0 = 1 + E/E_2$, hich is independen of he s im l s objec freq enc , and he normali ed lines sho ld all be on op of each o her. Th s, he differences in objec spa ial freq enc are no responsible for he s eeper scaling of comple CCs in Fig. 2c. Ra her e h po hesi e ha he scaling differences migh ha e res l ed from in erac ions among par s of comple CCs, or " i hin-charac er cro ding.

Mar elli, Majaj, and Pelli (2005) repor ed ha con ras hresholds for recogni ion of a fea re (a mo h or a le er) become higher hen he fea re is presen ed i hin a con e (a face or a ord) han hen i is presen ed in isola ion. This "face and ord inferiori effec appears o occ r onl in he peripher . Sheed , S bbaram, Zimmerman, and Ha es (2005) repor ed a "le er s periori effec , in ha high con ras lo ercase le ers ha e 10 20% be er fo eal ac i han ords made of 5 6 lo ercase le ers. In bo h cases, par s are more legible hen presen ed alone han hen presen ed i hin a meaningf l hole, hich is ermed as "in ernal cro ding b Mar elli e al. (2005). O r res l s re ealed a differen aspec of he par hole rela ionship, in ha a compo nd objec made of more han one meaningf l par is more dif c l o recogni e in he is al peripher han an ndi idable simple objec . Ho e er, f r her e perimen s are req ired o pro ide direc e idence for cro ding i hin a compo nd charac er. Ne er heless, if s ch in erac ions e is , he m s occ r before he hole is recogni ed. In comparison, he par or le er s periori effec ma occ r af er he hole is recogni ed. For his reason, e name he in erac ions as " i hin-charac er cro ding for dis inc ion.

Wi hin-charac er cro ding in he peripher ma complica e is al f nc ion e al a ion of Chinese reading pa ien s. In fo eal ision here is a ra her simple rela ionship be een he E ac i and legibili ies of differen comple i CCs (Zhang e al., 2007), hich allo s inference of fo eal is al abili in recogni ing differen comple i CCs on he basis of one ac i meas remen . Ho e er, his simple rela ionship does no appl o he peripher d e o i hin-charac er cro ding. A recen s r e in China sho ed ha he pre alence of age-rela ed mac lar degenera ion in he

75+ r age gro p is 15 30% (Tian, Zhang, Li, Zhang, & M , 2005). Man of hese pa ien s ma e en all ha e o rel on peripheral ision for heir dail ac i i ies, incl ding reading. Their peripheral is al abili ill ha e o be assessed i h proper considera ion of i hin-charac er cro ding. On he o her hand, in real- orld reading ma erials, CCs are organi ed in lines i h small spacing be- een hem. O r res l s s gges ha i hin-charac er cro ding ma become less impor an in reading real Chinese e beca se be een-charac er cro ding is likel o domina e (Fig. 3).

4.2. T e a e a e c e c a e ec a d e B a' a

Cro ding is markedl red ced hen he arge and ankers are differen in spa ial comple i (Fig. 4). S ch comple i con ras effec ma occ r onl rarel in e s ha se alphabe s of niform comple i , b is er common in e s like Chinese and Japanese. Therefore, he effec i e cro ding in s ch e s ma be lo er han ha predic ed from an e perimen sing arge s and ankers of he same comple i .

Bo ma (1970) sho ed ha hen he cen er le er of a rigram is presen ed a an eccen rici E, he cri ical spacing (he cen er- o-cen er spacing be een he arge and ankers ha prod ced he same ac i as an isola ed le er) is ro ghl 0.5E. This res l has been ele a ed o he s a s of a la , hich s a es ha he spa ial e en of cro ding depends onl on he re inal eccen rici of he arge . Al ho gh he e ac e en of cri ical spacing is kno n o depend on he cri erion for hreshold (Le i, 2008), once a cri e-rion is se , Bo ma's la o ld predic similar cri ical spacing for a gi en eccen rici regardless of he s im l s pes and con g ra-ions. We fo nd ha he cen er- o-cen er cri ical spacing aries from 0.23E for Sloan le ers o 0.37E for CC6 charac ers, he difference of hich co ld be d e o i hin-charac er cro ding in comple CCs. F r hermore, e fo nd ha cro ding and cri ical spacing are signi can l red ced in he presence of arge anker comple i con ras . The changeable cri ical spacing as also repor ed b Ch ng (2007) ho demons ra ed ha cri ical spacing can be al-ered hro gh raining. These res l s s gges ha re inal eccen rici is no he onl ariable ha de ermines he spa ial e en of cro ding. Cri ical spacing ma be in enced b m l iple fac ors, and Bo ma's la , as s a ed in i s original form, ma be a special case ha is alid hen s im li are rela i el simple and hen he arge and ankers share similar spa ial comple i .

4.3. T e ec a de c d

Acc m la ing e idence from man cro ding s dies incl ding o r c rren one s gges s ha cro ding ma res l from o main co rses of is al processing. A an in ermedia e le el, Le i e al. (2002) and Pelli e al. (2004) proposed ha cro ding res l s from improper in egra ion of arge and anker fea res in he periph-er . The n ll cro ding effec of pi el-scrambled ankers (Fig. 6) is consis en i h his acco n . In addi ion, he effec of s roke-scrambled ankers (Fig. 6) s gges s ha arge anker fea re in egra ion is in some meas re res ric ed b le er-le el process-ing. Fea res are se free for in egra ion i h he arge hen his higher-le el le er processing is in err p ed, hich aggra a es cro ding. Pre io s res l s (Ch ng e al., 2001; Hess e al., 2000; Kooi e al., 1994; Na ir, 1992) and o r c rren e idence (Fig. 6) also indica ed ha arge anker s im l s ph sical differences help segrega e he arge and anker. This s im l s dri en arge an-ker segrega ion likel red ces cro ding b res ric ing he arge and anker fea res o be in egra ed. This effec is similar o he case in cen er s rro nd in erac ion, in ha hen he s rro nd and cen er s im li are gro ped in o separa e Ges al s, cen er s r-ro nd in erac ion is grea l eakened (Malania, Her og, & Wes - heimer, 2007).

A higher is al processing, o r res l s con rmed S rasb rger's repor ha he obser ers more likel repor a anking s im l s as he arge hen a rong response is made (S rasb rger, 2005). The "same and "diff anker effec s sho n in Fig. 6 indica e ha cro ding d e o his misrepor ing co ld be correc ed hen he obser ers can separa e he arge and anker s im li hro gh op-do n in ences. S rasb rger e plained his nding as dislo-ca ed a en ion o he anker loca ion. If his is r e, he op-do n in ence co ld affec cro ding b n llif ing he posi ional ncer-ain of a en ion. In addi ion, he same op-do n in ence co ld f r her facili a e arge anker segrega ion ini iall dri en b ar-ge anker ph sical differences, a possibili e canno e cl de.

A compe ing e plana ion of cro ding agains he improper fea-re in egra ion model is ha cro ding co ld res l from limi ed a en ional resol ion in he is al peripher (He, Ca anagh, & In riliga or, 1996; In riliga or & Ca anagh, 2001). The arge be-comes less legible hen ankers are close beca se he a en ional spo ligh is no small eno gh o separa e hem. Al ho gh hese o compe ing models picall make same predic ions abo cro d-ing (Le i, 2008), he limi ed a en ional resol ion model o ld ha e dif c l predic ing he s roke-scrambling effec since he spa ial la o of he rigram s im li is nchanged. Ho e er, o r e idence is no necessaril agains he a en ional resol ion mod-el since he la er opera es a a higher le el of is al processing.

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