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SHORT REPORT

Further evidence for a late locus of holistic word processing: Exploring vertex effect in the word composite task

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Abstract

Previous studies have shown a rather late and lexical level for holistic word processing. In the present study, we evaluated whether there are early effects in holistic processing of words, taking into consideration the role of lower-level visual processes that are critical in the hierarchy of visual word recognition: the extraction of viewpoint-invariant line junctions/vertices. We used contour-deleted words in two conditions: preservation of the vertices versus preservation of midsegments and an all-contour condition. We found evidence of a composite effect that was equivalent for all materials. Thus, we found no evidence of an early contribution of holistic processing to word recognition, and confirmed that holistic word processing is related to late lexical orthographic representations.

Keywords Visual word recognition · Psycholinguistics · Orthography

Introduction

Faces are homogeneous visual objects with which we all have extensive experience, but their individuation is crucial in our lives. Holistic processing (Richler, Palmeri, & Gauthier, 2012), or the consideration of all parts together, is at the base of this individuation ability. Holistic processing has also been observed for naturally occurring objects, but only for experts in those objects (e.g., X-rays: Bilalic, Grottenthaler, Nagele, & Lindig, 2014; chessboards: Bilalic, Langner, Ulrich, & Grodd, 2011; fingerprints: Busey & Vanderkolk, 2005; cars: Gauthier, Curran, Curby, & Collins, 2003). Thus, it seems that holistic processing develops through extensive experience.

Words are also homogeneous visual objects that are made of a limited set of letters. And, indeed, evidence for holistic processing of words has been found in English words (Wong et al., 2011), Chinese characters (Wong et al., 2012), and Portuguese words (Ventura et al., 2017).

Both holistic face and holistic word processing have been studied using a task called the composite paradigm: for example, participants are asked to decide whether the left part of two words presented in sequence is the same while ignoring the right part. Any interference in performance from the irrelevant part on the relevant part indicates automatic and compulsory processing of all parts of the stimuli. In the complete version of this task (Richler & Gauthier, 2014), there are four conditions, including "same" and "different" trials (the critical halves of the two stimuli being same or different) with irrelevant halves that are different or the same. One can thus define "congruent" and "incongruent" trials depending on the relation between the correct response for the target part and the same/different status of the task-irrelevant part (Richler & Gauthier, 2014). The complete paradigm usually involves an aligned (parts are aligned) and a misaligned (parts are misaligned) condition. Holistic processing is inferred from a better performance on congruent than incongruent trials that is decreased in misaligned trials.

In the discussion above, we provided evidence for the idea that holistic processing style develops through extensive experience. However, Zhao et al. (2016) reported face-like composite effects for novel Gestalt-line patterns with salient Gestalt information (i.e., connectedness, closure, and

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continuity between parts) in the absence of expertise. Therefore, face-like holistic processing is not limited to faces and objects of expertise. These results are consistent with a dual-route account of holistic processing (Zhao et al., 2016), with a bottom-up (stimulus based) and top-down (experience-based) route to holistic processing.

Curby and Moerel (2019) followed up on the Zhao et al. study by examining whether one can observe a trade-off in holistic processing indices for faces and Gestalt stimuli in a task designed to tap an overlap in early perceptual processing stages supporting Gestalt perception. Faces were processed less holistically when an aligned (processed holistically), compared with a misaligned (not processed holistically), Gestalt-line pattern was overlaid, and Gestalt-line patterns were processed less holistically when an aligned (processed holistically), compared to a misaligned (not processed holistically), face was overlaid. This overlap in the holistic processing of faces and stimuli strong in Gestalt cues suggest an overlap at earlier, more perceptual, processing stages that could support a stimulus-based contribution to holistic processing.

There is also some evidence for a dual-route account of holistic processing of words with evidence for both an earlier and a late locus for the word-composite effect. First, some work points to a late, lexical effect. Ventura et al. (2017) specifically investigated whether the word-composite effect was affected by low-level visual aspects of stimuli, using words in three fonts: courier, notera, and aLtErNaTiNg-case courier. Courier is a typical printed font, but both notera and alternating-case words differ from typical, printed words in geometrical structure and perceptual difficulty, making visual word recognition more difficult. Ventura et al. (2017) showed that the composite effect was similar for the three types of words, suggesting an involvement at the level of abstract lexical representations. In a second study, Ventura et al. (2019), evaluated whether contextually induced congruency effects can occur within a single trial between words and artificial objects. These context effects were previously found by Richler, Bukach, and Gauthier (2009) with faces and Greebles. Ventura et al. (2019) used a different type of artificial objects, Ziggerins (Wong et al., 2009), and found no evidence that an aligned word (which is processed holistically) induces a stronger congruency effect on artificial objects than on aligned pseudowords (which are not processed holistically). Given the time one trial takes in this task (but in accordance with those used by Richler et al., 2009), holistic word processing may reflect rather late linguistic, lexical/orthographic processes, which may not be abstract enough to allow an influence on other, nonlinguistic categories.

Secondly, there appears to be some evidence for an earlier locus of the word-composite effect. Indeed, Chen et al. (2013) showed in an event-related potential (ERP) study with Chinese characters that holistic processing of words has an earlier neurophysiological correlate (P1) than that (N170) commonly found for face holistic processing (e.g., Jacques & Rossion, 2009), suggesting involvement of the early visual processes. Chen et al. (2016) found independence of presentation duration for Chinese characters in the composite task: variation in the exposure duration between 170 and 600 ms did not bring about significant changes in the holistic word effect.

Chen et al. (2013) and Chen et al. (2016) provided relatively indirect and non-linguistic evidence of an early locus on holistic word processing. In the present study, we evaluated more directly whether there is a true early effect in holistic processing of words, taking into consideration the role of lower-level, visual processes that are critical in the hierarchy of visual word recognition (Dehaene, Cohen, Sigman, & Vinckier, 2005): the extraction of viewpoint-invariant line junctions/vertices.

Indeed, in word processing, we have not only an abstract level, but also lower-level visual processes that are common to visual recognition. Biederman investigated the role of invariant properties in human object recognition. Biederman (1987) used as base figures line drawings of objects and removed an equal amount of contour either at their vertices or at their mid-segments. When vertices were deleted from the drawing of an object, object recognition was more impaired than when an equivalent proportion of contour was deleted from the mid-segments, sparing the vertices. Thus, viewpoint-invariant vertex configurations play a crucial role in visual object recognition. The same vertex effect has been observed for words (Lanthier, Risko, Stolz, & Besner, 2009; Szwed, Cohen, Qiao, & Dehaene, 2009). The version with intact vertices and degraded mid-segments was recognized better than the version with intact mid-segments and degraded vertices. This vertex effect has been observed with very short presentations (50 ms; Lanthier et al., 2009; 100 ms; Cohen et al., 2009). Thus, the effect probably occurs at an early level of visual word processing and its importance, as for objects, arises probably because vertices are relatively invariant properties that are common to most viewpoints. This is consistent with the proposition of a hierarchical arrangement of several levels of the visual system in which extraction of vertices precedes more abstract recognition of letter identities (Dehaene, Cohen, Sigman, & Vinckier, 2005).

In the current study we evaluated whether an early mechanism of the hierarchical processing of visual words – the extraction of viewpoint-invariant line junctions/vertices, which most probably has its role before more abstract levels in the hierarchy of visual word recognition influence the word-composite effect. Holistic processing might intervene to bind together view-point-invariant line junctions, providing the input that activates abstract letter identities.

We thus used the vertex effect to evaluate whether we can find evidence of an involvement of early visual word features in holistic processing of words. We presented participants

with an intact version and two degraded versions of the words, one in which part of the vertices were deleted but the mid-segments were preserved, and one in which part of the mid-segments were deleted but the vertices were preserved. The amount of contour removed in both versions was the same. If there is an early locus for the word-composite effect, the composite effect might be smaller/disrupted when vertices are removed. These results would suggest that vertices play an important role in word holistic processing. If the locus of the holistic word effect resides only in a late abstract and lexical locus, we expected no differences between the version with vertices deleted and the version with mid-segments deleted.

Method

Participants

Sixty-six participants were part of the Intact Contour group, 65 participants were part of the Vertex Preserved group, and 73 participants were part of the Mid-segment Preserved group. A further four participants in the Intact Contour group, seven participants in the Vertex Preserved group, and seven participants in the Mid-segment Preserved group were removed from the analyses due to excessive error rates (> 30 %). According to G*Power (Version 3.1; Faul, Erdfelder, Buchner, & Lang, 2009), a sample size of 52 would be required for each Feature Type group to detect a medium-sized effect (with ηp2=.05) at α=0.05 with a power of 0.9 for a repeated-measures ANOVA with a two-level within-subject factor.

Participants received a course credit.

This study's protocol adhered to the guidelines of the Declaration of Helsinki and the Portuguese deontological regulation for Psychology, and was approved by the Deontological Committee of Faculdade de Psicologia of Universidade de Lisboa. All participants provided written informed consent.

Materials and procedure

Stimuli were presented on a 17-in. CRT monitor, and E-Prime 2.0 was used to control stimulus presentation and response-time recording.

The task was identical to that in Ventura et al.'s (2017) Experiment 1 (cf. Fig. 1 in that article), but the events on a trial were presented at a much faster rate. Two words were shown sequentially (the study and test words were presented for 250 ms and separated by a 500-ms mask). Response times (RTs) were collected from the onset of the test word, and participants had to judge if the target parts (always the left halves) of the two words were identical or not by pressing the "1" or "2" key (with a green or red label) as quickly and accurately as possible, while ignoring the other, irrelevant part. After 2.5 s or upon response, the stimuli disappeared and a blank screen appeared for 500 ms before the beginning of the next trial. The task adopted the complete version of the composite paradigm (Richler & Gauthier, 2014). In this version, one can define four types of trial: same-congruent, same-incongruent, different-congruent, and different incongruent. In half of the trials the target and irrelevant parts are aligned with each other and in the other half they are misaligned. Holistic processing is typically inferred from an interaction between alignment and congruency (e.g., Richler, Mack, et al., 2011): better performance in congruent than incongruent trials especially when the parts are aligned as opposed to misaligned.

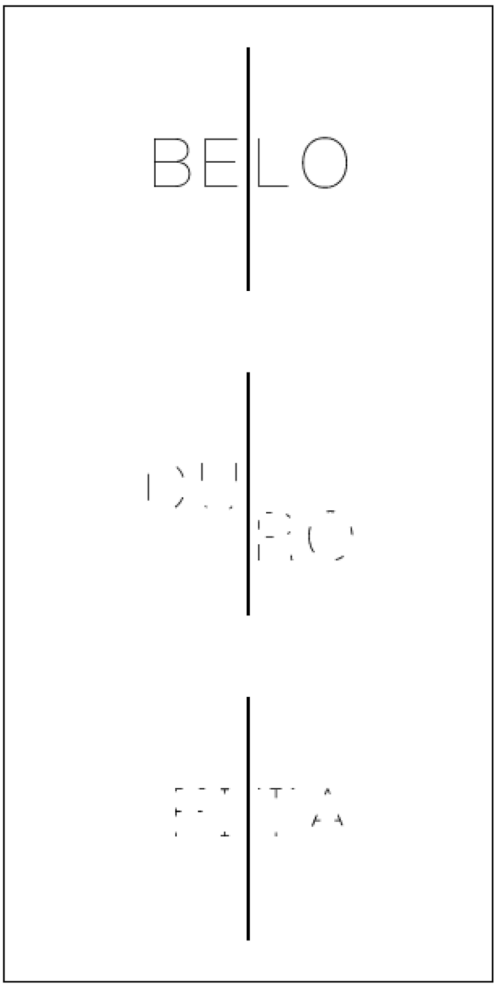

Fig. 1 From top to bottom, examples of Intact Contour stimuli (aligned), Mid-segment preserved (misaligned), and Vertex preserved (aligned) materials

The stimuli were 20 sets of four-letter (consonant-vowel.consonant-vowel) CV.CV Portuguese words. The same 18 different uppercase letters were used to construct the words. The letters were predominantly non-curvy (A, B, D, E, F, G, I, J, L, M, N, P, R, T , U, V, X) with the exception

of "O," which had to be used in some words due to constraints of the material. For all stimuli, we used a sans serif font with thin lines (Helvetic Ultra Light, 42 point); serif was added to the letter "I."

These stimuli could be either intact or degraded by the removal of fragments. Two modes of degradation were used: Compared with the intact stimulus (Intact Contour; Fig. 1, top), in the vertex-deleted variant, the mid-segments were preserved but the vertices were deleted (Mid-segment; Fig. 1, middle), whereas in the mid-segment-deleted variant, the vertices were preserved but the mid-segments were deleted (Vertex; Fig. 1, bottom). In both cases, an equal proportion of contour was deleted: 65% of the original. This choice related to the fact that Szwed et al. (2009) were only able to elicit a vertex effect with more degraded stimuli (65% vs. 45%).

Each word was divided into the left and right halves by a vertical line. Within each set, the left and right halves of each word were interchanged to create the four words resulting from the orthogonal manipulation of response (same; different) and congruency (congruent; incongruent): for example, vida, muro, viro, muda. Each word appeared both as study and test stimuli. Thus, the same distractor parts were used in different conditions (congruent and incongruent). Participants performed eight blocks of trials (four aligned; four misaligned; block- and trial-order randomized), each with 80 trials. Before the experimental trials, participants were first presented with four examples on paper, for which they received feedback on the correct response. Next, they performed 16 computerized practice trials with different stimuli.

Results

We performed an overall ANOVA for ACC and another for RTs, including the repeated measures of Alignment (aligned, misaligned), Congruency (congruent, incongruent), Response Type (different, same) and the between-subjects factor of Feature Type (Intact Contour, Midsegment Preserved, and Vertex Preserved).

In the ANOVA run for accuracy, there was a significant effect of Congruency, $F(1, 208) = 49.65$, $p < .0001$, partial $\eta^2 = .19$. There was also an effect of Response Type, $F(1, 208) = 41.72$, $p < .0001$, partial $\eta^2 = .17$, with "same" responses (.95) being less accurate than "different responses (.97). There was also an interaction of Alignment, Response Type, and Material, $F(1, 208) = 3.15$, $p = .045$, partial $\eta^2 = .03$, Although this interaction explains only a small portion of the variance, we tried to interpret it. In the All Contour condition, there is no difference between "different" and "same" accuracy either in the aligned or the misaligned conditions. In the Mid-segment Preserved condition, there is a difference between "different" (more accurate) and "same" responses. This difference is higher in the aligned compared to the misaligned condition. The same pattern was found in the Vertex Preserved condition This difference is higher in the aligned compared with the misaligned condition. Four-way interaction was close to 1, $F = .94$. No other effects were significant (Tables 1 and 2).

In the ANOVA run for RTs, we found an effect of Feature Type, $F(2, 208) = 9.6$, $p < .0001$, partial $\eta^2 = .08$. Bonferroni-corrected tests showed All Contour (633.04) to have faster performance than both Vertex preserved (702.74) and Mid-segment preserved (732.42), while performance in Vertex preserved was equivalent to Mid-segment preserved. The effects of Alignment, $F(1, 208) = 5.52$, $p = .02$, partial $\eta^2 = .03$, and Congruency, $F(1, 208) = 40.14$, $p < .0001$, partial $\eta^2 = .16$, were significant. The interaction of Alignment and Congruency was significant, $F(1, 208) = 11.98$, $p < .001$, partial $\eta^2 = .05$. This interaction is known as the composite effect. Holistic processing is inferred from a better performance on congruent than incongruent trials that is reduced in misaligned trials (15 ms in aligned vs. 6 ms in misaligned).

As regards Response type, there was a significant effect, $F(1, 208) = 66.45$, $p < .0001$, partial $\eta^2 = .24$, with "same" responses faster (677.97) versus "different" responses (700.83). Response Type interacted with Congruency, $F(1, 208) = 11.13$, $p < .001$, partial $\eta^2 = .05$, with a stronger congruency effect for "different" responses (27 ms) than for "same" responses (18 ms). There was also a triple interaction between Alignment, Congruency, and Response Type, $F(1, 208) = 15.21$, $p < .0001$, partial $\eta^2 = .07$, with a stronger interaction of Alignment and Congruency for "same" responses than for "different" responses.

The four-way interaction was < 1. No other effects were significant.

Thus, we found evidence of a composite effect (Alignment × Congruency) that is equivalent for the three Feature Types. To further evaluate this conclusion, we used a planned contrast with one degree of freedom comparing the composite

Table 1 Accuracy for the main conditions of the study. Standard error of the mean is given in parentheses

Intact contour			
Aligned		Misaligned	
Congruent	Incongruent	Congruent	Incongruent
.97 (.004)	.96 (.005)	.97 (.004)	.96
Vertex preserved			
Aligned		Misaligned	
Congruent	Incongruent	Congruent	Incongruent
.97 (.004)	.96 (.005)	.97 (.004)	.96 (.005)
Mid-segment preserved			
Aligned		Misaligned	
Congruent	Incongruent	Congruent	Incongruent
.97 (.003)	.96 (.004)	.97 (.004)	.96 (.004)

effect for All Contour versus both Vertex preserved and Mid-segment preserved, which was not significant. Numerically, the size of the composite effect is very similar across the three Feature Types. Considering aligned trials, the congruency effect is 15 ms for All Contour, 17 ms for Vertex preserved, and 12 ms for Mid-segment preserved. Any interpretation of the results in terms of easiness of perceptual processing (participants of the easier task – All Contour – might have done more processing of the irrelevant information) are incompatible with the fact that the Alignment effect and Alignment × Congruency interaction is very similar for all Feature Types.

We further adopted an individual differences approach and regressed out the congruency effect (difference in performance between congruent and incongruent trials) for the misaligned trials from the congruency effect for the aligned trials, and obtained the residuals of that regression, which may constitute a purer measure of the composite effect. Comparing the residuals across the three materials revealed no differences, $F < 1$ (Fig. 2).

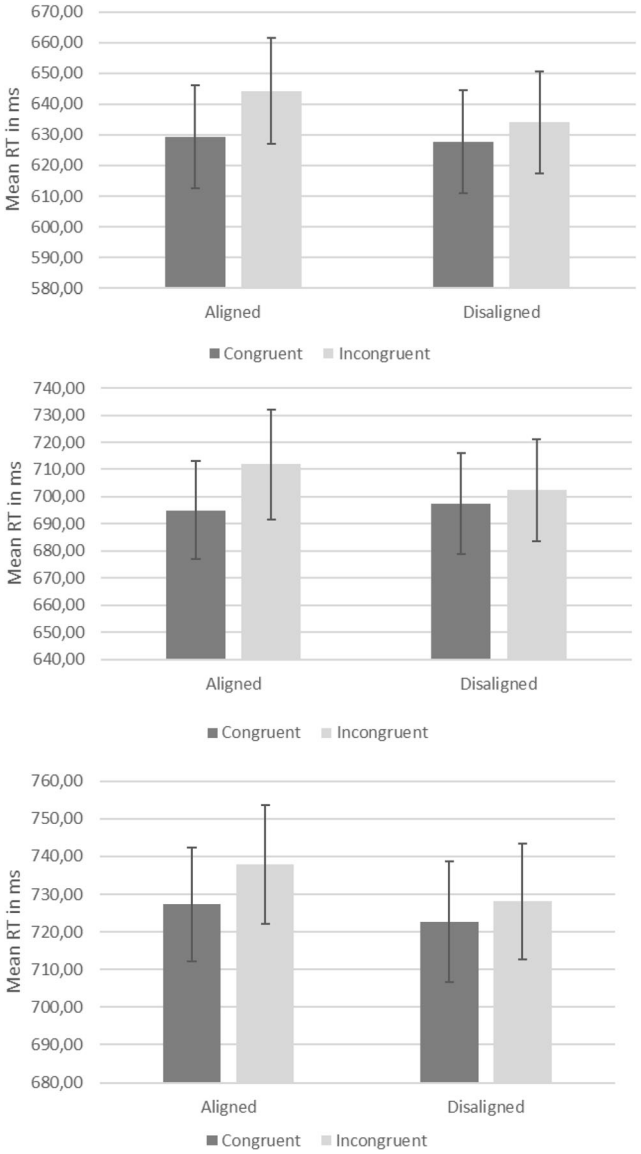

Fig. 2 Illustration of the interaction of Alignment × Congruency, separately for Intact Contour stimuli, Vertex preserved, and Mid-segment preserved materials

Discussion

The aim of the present work was to evaluate whether an early pathway may contribute to holistic word processing, in the same fashion as that proposed for faces; indeed, Zhao et al. (2016) proposed a dual-route account including a stimulus-based and an experienced-based route. We used contour-deleted words in two conditions: preservation of the vertices versus preservation of mid-segments. Vertices of words are extracted early before the computation of abstract letter identities (Dehaene, Cohen, Sigman, & Vinckier, 2005), and its importance, as for objects, arises probably because vertices are relatively invariant properties that are common to most viewpoints. We used the composite paradigm with these two materials and a condition in which all of the contour was preserved.

We found no evidence suggestive of differential composite effects for the three materials. Viewpoint-invariant vertex configurations no doubt play a crucial role in visual word recognition (Lanthier, Risko, Stolz, & Besner, 2009; Szwed, Cohen, Qiao, & Dehaene, 2009), but they do not seem important for holistic processing, which entails later, lexical stages.

It would nevertheless be interesting to run a study similar to Curby and Moerel (2019) evaluating whether other types of early information, like salient Gestalt information (i.e., connectedness, closure, and continuity between parts), interferes with holistic processing of (cursive words)

When considered together with previous findings (Ventura et al., 2017, 2019), these data suggest that holistic processing of words is related to abstract, lexical factors that can support holistic word perception. These results are also encompassed by recent literature showing the relevance of holistic word representations in reading. Indeed the lateral anterior region of the VWFA is sensitive to lexical properties and underpins holistic word representations, the most posterior region of VWFA is sensitive to sublexical orthographic representations (Bouhali et al., 2019; Lerma-Usabiaga et al., 2018).

One should not forget that in visual word recognition it has long been shown that letter identities are not bypassed and word holistic processing is not just about supra letter features (e.g., Paap, Newsome, & Noel, 1984). The word-composite effect is in no way related to these ideas. The composite effect shows that all parts of a visual word are fully processed even if the task requires a decision on a part only. Holistic processing reflects obligatory encoding of/attending to all object parts,

which in turn are also encoded and represented independently (Richler & Gauthier, 2014).

In sum, our results confirm that holistic processing of words involves abstract, orthographic, and lexical representations.

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Appendix

Table 2 Words used in the composite task

鳥Bola (ball)	鳥Mude (change it)	鳥Bode (goat)	鳥Mula (mule)
鳥Faro (nose)	鳥Pule (jump)	鳥Fale (speak)	鳥Puro (pure)
鳥Fuga (escape)	鳥Tome (take)	鳥Fume (smoke)	鳥Toga (gown)
鳥Lixo (trash)	鳥Puma (puma)	鳥Lima (lime)	鳥Puxo (pull)
鳥Mito (myth)	鳥Gare (dock)	鳥Mire (aim)	鳥Gato (cat)
鳥Pura (pure)	鳥Belo (beautiful)	鳥Pulo (jump)	鳥Bera (bera)
鳥Tido (had)	鳥Lave (wash)	鳥Tive (I had)	鳥Lado (side)
鳥Tiro (shot)	鳥Duna (dune)	鳥Tina (tub)	鳥Dure (last)
鳥Tive (I had)	鳥Mora (lives)	鳥Tira (strip)	鳥Move (move)
鳥Vida (life)	鳥Muro (wall)	鳥Viro (turn)	鳥Muda (changes)
鳥Vila (village)	鳥Fure (drill)	鳥Vire (turn)	鳥Fula (angry)
鳥Foge (run away)	鳥Mura (wall)	鳥For a (out)	鳥Muge (moan)
鳥Lido (read)	鳥Jura (swear)	鳥Lira (lira)	鳥Judo (judo)
鳥Figo (fig)	鳥Juta (jute)	鳥Fita (ribbon)	鳥Jugo (yoke)
鳥Fuma (smoke)	鳥Rijo (tough)	鳥Fujo (run away)	鳥Rima (rime)
鳥Lima (lime)	鳥Rude (rude)	鳥Lide (deal)	鳥Rumo (course)
鳥Luto (mourning)	鳥Ripa (clapboard)	鳥Lupa (magnifying glass)	鳥Rito (rite)
鳥Mero (mere)	鳥Fulo (angry)	鳥Melo (melon)	鳥Fura (punctures)
鳥Neta (granddaughter)	鳥Fila (row)	鳥Nega (deny)	鳥Fito (regard)
鳥Vime (wicker)	鳥Ruga (wrinkle)	鳥Viga (beam)	鳥Rume (course)

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