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Article

Comparative Analysis of Networks of Phonologically Similar Words in English and Spanish

Samuel Arbesman¹, Steven H. Strogatz² and Michael S. Vitevitch^{3,*}

¹ Department of Health Care Policy, Harvard Medical School, 180 Longwood Avenue, Boston, MA 02115, USA; E-Mail: arbesman@gmail.com

² 223 Kimball Hall, Cornell University, Ithaca, NY 14853, USA; E-Mail: shs7@cornell.edu

³ Department of Psychology, 1415 Jayhawk Boulevard, University of Kansas, Lawrence, KS 66045, USA

* Author to whom correspondence should be addressed; E-Mail: mvitevit@ku.edu.

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Abstract: Previous network analyses of several languages revealed a unique set of structural characteristics. One of these characteristics—the presence of many smaller components (referred to as *islands*)—was further examined with a comparative analysis of the island constituents. The results showed that Spanish words in the islands tended to be phonologically and semantically similar to each other, but English words in the islands tended only to be phonologically similar to each other. The results of this analysis yielded hypotheses about language processing that can be tested with psycholinguistic experiments, and offer insight into cross-language differences in processing that have been previously observed.

Keywords: language network; comparative analysis; English; Spanish

1. Introduction

Network analysis has been used to examine various aspects of language. With words constituting the vertices of a network, edges have been placed between vertices if the words are semantically related (*i.e.*, similar meanings) [1–5] or syntactically related [6–8]. Previous network analyses have also examined the structure that exists among words that are related in terms of their orthography (*i.e.*, how the words are spelled) or phonology (*i.e.*, how the words are pronounced) [9–11]. Using a metric

of phonological similarity that is widely used in Psycholinguistics [12], Vitevitch [13] created a network of English word-forms (WF) from approximately 20,000 well-known words. Rather than place edges between vertices if the words shared a syllable (as in [9,10]) edges in this network were placed between vertices if those words differed by a single phoneme, resulting in edges being placed between the word *cat* and the words *at*, *bat*, *mat*, *rat*, *scat*, *pat*, *sat*, *vat*, *cab*, *cad*, *calf*, *cash*, *cap*, *can*, *cot*, *kit*, *cut*, and *coat* (as well as other relevant words).

Analysis of the English WF network in [13] revealed several unique characteristics. For example, the network of English WF consisted of a giant component that was much smaller (containing 34% of the vertices) than the giant components typically observed in the literature (80–90% [14]), as well as a large number of smaller components, referred to as lexical islands, containing words that sounded similar to each other—such as *faction*, *fiction*, and *fission*—but not to other words in the largest component, and a large number of vertices, referred to as lexical hermits, that had no edges, indicating that they did not sound like any other word in the network: *spinach*, *obtuse*, etc.

Further analysis of the largest component in the English WF network revealed that it exhibited small-world characteristics [15], as well as a degree distribution that deviated from a power-law, and assortative mixing by degree. The observation of assortative mixing by degree in the English WF network is interesting for two reasons. First, disassortative mixing by degree was observed in a network of syntactic relationships among words [8], highlighting the importance of using the techniques of network science to examine multiple aspects of language. Second, although assortative mixing by degree has been observed in social networks, the value of the correlation among connected vertices was larger ($r = 0.6$) than is typically observed in social networks ($r = 0.1 - 0.3$ [16]). The different patterns of mixing by degree observed in phonological and syntactic networks may reflect the different constraints governing syntactic versus phonological relationships among words (see [17] for an example of how imposing additional constraints in a network can influence the emergence of certain network features). Furthermore, the different patterns of mixing by degree may also present network and cognitive scientists a unique opportunity to explore a question of common interest to mutual benefit, as suggested by the members of a Virtual Round Table discussing the ten leading questions for network research: Why are social networks all assortative, while all biological and technological networks disassortative? [18].

Given the uniqueness of these characteristics in the lexical network compared to what is typically observed in other networks, it was important to verify that these characteristics of the English WF network were not artifacts of the English language. Therefore, the WF networks of several other languages were also examined for comparison [19]: Spanish, Mandarin, Hawaiian, and Basque. These languages differed from English in a number of ways, including language family (e.g., Indo-European, Sino-Tibetan, etc.), phoneme inventory (the number of consonants and vowels in each language), and morphological productivity. Despite the differences among the languages (and size of the lexicons examined), the same characteristics that were observed in the English WF network were also observed in the WF networks for the other languages examined. How these unique characteristics contribute to the robustness of the language networks was also explored [19], with the results of those simulations having implications for the robustness of language processing under normal conditions, as well as under conditions in which the network has been damaged (as might occur during temporary word-finding problems, or neurological conditions such as aphasia).

2. Comparative Analysis of English and Spanish Networks

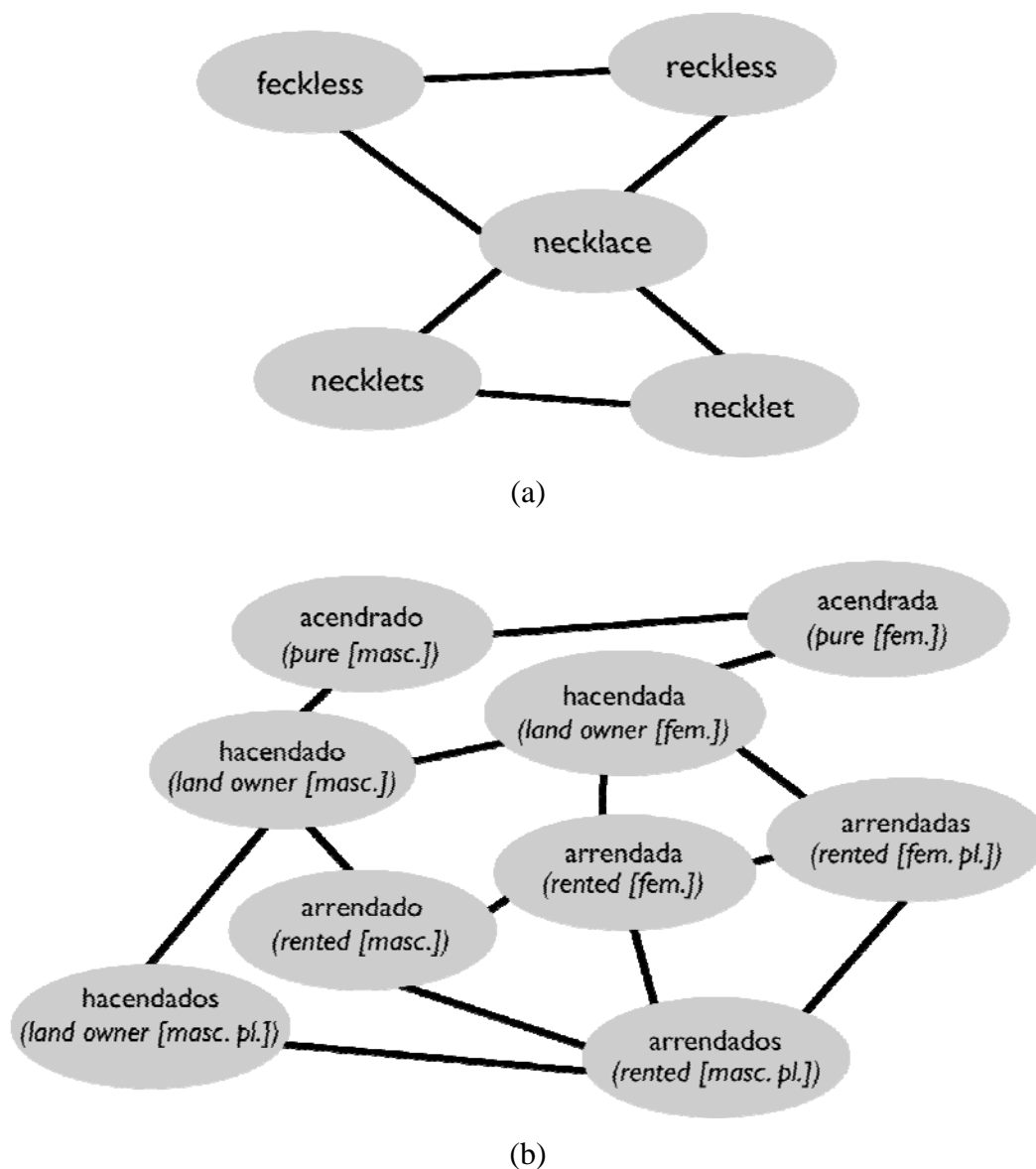
Psycholinguistic experiments have shown that the network characteristic of degree influences in English the cognitive processes of word recognition [12], word production [20], and word learning [21]. (Note that in the psycholinguistic literature degree is referred to as *neighborhood density*.) Interestingly, degree has different influences in Spanish compared to English [22,23], suggesting that the same network structure might have a different influence in a different language as a function of other “structural” characteristics that are not captured in current network measures (e.g., clustering coefficient, degree distribution, *etc.*). Recall that the lexical networks of several languages consisted of a small giant component (which we will refer to as the *giant component*), several smaller components (which we will refer to as *islands*), and many non-connected vertices (which we will refer to as *lexical hermits* [19]). We present here the results of a novel analysis of the constituents of the islands, in addition to the giant components, to expose subtle differences between English and Spanish, which might provide insight into the differences observed in psycholinguistic experiments in the two languages. Similar analyses of the characteristics of the constituents of islands and giant components might prove useful in understanding complex systems in other domains.

2.1. Method

We randomly selected 100 words from each of the giant components of the Spanish and the English WF networks (where for this study, the WF network of English was created using a more complete corpus of words [24]), and a single word from each of the 100 largest islands in both the English and Spanish networks [19]. Each word and all of the vertices immediately connected to it (*i.e.*, a 1-hop neighborhood) were examined by hand to determine if a word and its neighbor were related in their derivational or inflectional morphology. An example of a lexical island from each language is presented in Figure 1, and the words from the ten largest islands are listed in the Appendix.

Derivational morphology changes the meanings of words by adding a morpheme (or unit of meaning), such as changing the adjective *good* to the noun *goodness*. In contrast, in inflectional morphology a morpheme is added to tag the word with additional meaning, such as person, number, tense, case, or gender. For example, the English words *dog* (singular) and *dogs* (plural) differ in the inflectional morpheme *-s*, denoting a difference in number. Note that every language does not mark every distinction. While it is mandatory to mark number in English nouns, such a distinction is not made in Japanese. Similarly, and more relevant to the present analysis, marking (grammatical) gender in nouns is mandatory in Spanish (all nouns are typically designated as either masculine or feminine), but is much less prevalent in English (found in loanwords like *actor/actress*, or pronouns like *he/she/it*).

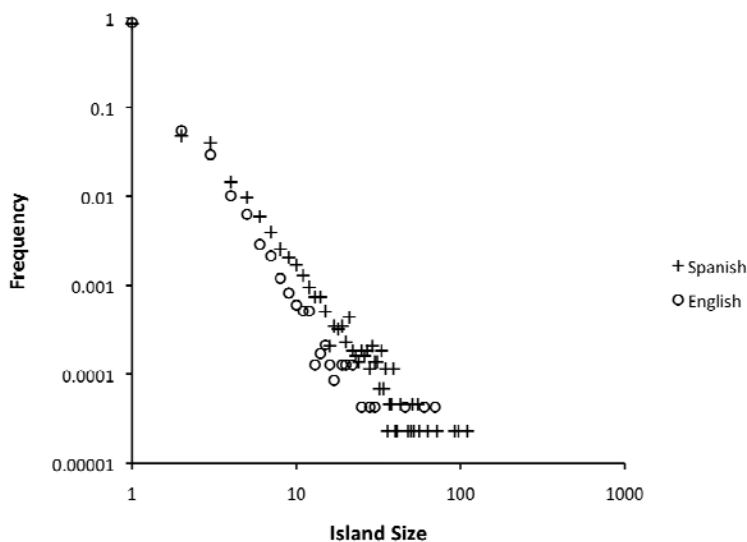
Figure 1. (a) A small island from English. Only the words 'necklet', 'necklets', and 'necklace' are related semantically (and, in fact, 'necklet' and 'necklace' are related derivationally). (b) An island from Spanish (with the root meanings below each word). While there are nine words, it can be seen that there are only three root meanings.



2.2. Results

A distribution of the frequency of all components smaller than the giant component can be seen in Figure 2, as plotted on a log-log scale, where they both adhere to a general straight line, that can be fit by power laws with exponents -2.3 (Spanish) and -2.5 (English). Power-law distributions have been observed in many aspects of language, and have been attributed to numerous causes [25,26]. Future analysis of a larger sample of languages is necessary to understand the distributions observed in the present case.

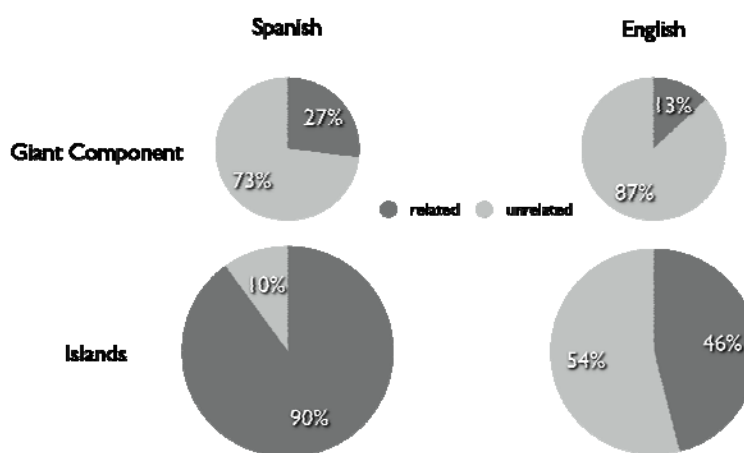
Figure 2. Component size distribution for islands in both Spanish and English. The giant components for both languages are not shown, though are of the following size: 44,832 (Spanish) and 23,922 (English).



Differences in the extent to which (inflectional) morphology is used in English and Spanish can be seen in Figure 3, and may have interesting implications for the structure and dynamics of the network. Recall that edges were placed between vertices in the networks based only on the phonological similarity of words (as defined by the one-phoneme metric). However, as can be seen in Figure 3, in both the islands and giant component, Spanish has a larger proportion of word pairs that are also morphologically related to each other than English.

The larger proportion of Spanish words that are similar phonologically and morphologically—sharing not just several sounds but also several semantic features—might facilitate the retrieval of the correct word-form from the lexical network. Even if the wrong phonological word-form is retrieved (*hacendada* instead of *hacendado*; the words differ only in gender), the common semantic information in the words may enable the language processing system to recover from the error. However, in the case of English, where words tend to be only phonologically similar, recognition of the spoken word might be more difficult, as the target word must be distinguished from neighbors that may have very different meanings (compare *reckless* and *necklace*). With such different meanings among neighboring vertices in English, perceptual errors might be more costly in English than in Spanish. Given the differences in the characteristics of the two languages, and the different costs in the two languages associated with a phonological error, different (but equally efficient) processing strategies might be implemented in the two languages (see [22,23]).

Figure 3. Morphological relationships between neighbor word pairs in the giant component and the 100 largest islands in Spanish and English.



3. Conclusion

From the novel analysis of the two language networks reported in Section 2, one can derive the testable prediction that words with high degree will be retrieved more quickly than words with low degree in languages that have a confluence of phonological and semantic networks, similar to Spanish. In languages similar to English, in which these cognitive networks are uncorrelated, words with high degree should be retrieved more slowly than words with low degree.

The present analysis of network structure not only provides cognitive scientists with testable predictions regarding the recognition of words across different types of languages, it may also provide network scientists with a new way to categorize complex networks in other domains (see Virtual Round Table: Are there further statistical distributions that can provide insights on the structure and classification of complex networks? [18]). Furthermore, the confluence of phonological and semantic information in this analysis points to the importance of understanding the structure and dynamics of multigraphs in addition to graphs with a single class of edges. Moreover, orthographic information may also influence phonological representations and the recognition of spoken words [27]. Finally, the domain of language provides cognitive and network scientists a unique opportunity to collaborate to their mutual benefit to understand the structure and dynamics of complex systems more generally [28].

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Appendix

Words in the largest ten islands in both Spanish and English. Note that the sizes of the English islands decay more quickly than the sizes of the Spanish islands:

Spanish

1. (111 words) presentirse, preguntarte, presentaron, presenten, preguntarles, presentable, presentado, presentaros, preguntar, preguntaste, presentada, preguntaros, presuntos, presentado, preguntara, preguntaré, preguntaron, presentaran, presentíamos, presentarlas, preguntan, pregúntesme, preguntado, presunto, presentadas, pregúntenle, presunta, presentarte, presentida, preguntando, presentarme, presentan, presentaba, pregunta, pregunté, presentadores, presentadorta, preguntador, pregúntale, preguntó, preguntas, preguntarme, presentase, presentarlo, presentarle, presentimos, presentarla, presentando, presentarnos, presentar, preguntados, presentarlos, presuntas, preguntarlo, preguntona, preguntarle, presentadora, preséntate, presentamos, preguntarnos, preguntase, preguntaba, presentas, preguntan, presentóse, presentir, preguntadas, presentadoras, pregúntese, presentado, pregúntate, pregúntelo, presentiría, pregúntele, presentaré, presiento, presentara, preguntada, presente, presentidos, preguntas, presentía, pregunten, presentables, preguntarse, presentarles, presentaban, presentador, presentas, presenten, presentirlo, presentaste, preguntole, presentes, presentaría, preguntaras, preguntaban, preguntamos, preguntaran, preguntabas, preguntemos, presentados, preguntaría, presentían, presentarse, presentarían, preguntón, presentó, presentí, presenté, presenta

2. (98 words) consolaban, consolarle, consumados, consolarla, consolarlo, consumían, consultar, consolarse, consolarles, consoladoras, consultivas, consultante, consultan, consumando, consultas, condolidos, consumimos, consolando, consolador, consultando, conjuntivo, consolada, consolado, consumidas, consuntivos, consultaban, consultivos,

consumíamos, consoladores, consultadas, consultado, consultados, consumaban, consolarme, consultarlo, consultarla, consultoras, consultarle, consultora, consultarte, consumen, consúltalo, consolidó, consolida, consolide, consolar, consoladora, consumada, conjuntivos, consumado, consolarlas, consolarla, consolarte, consumidos, consolidan, consultarme, consulten, consumí, consumido, consolas, consumó, consuma, consumida, consume, consumidor, consolidar, consultaba, conjuntivas, consultarlas, consulado, consumaba, consumía, consumos, consultamos, consumé, consultor, consulados, consultada, consumamos, conjuntiva, consultara, consultaría, consultaré, consumir, consolaba, consoló, consola, consultarlos, consumió, consuno, consumir, condolido, consulta, consulté, consultivo, consultiva, consuman, consultó

3. (93 words) anunciantes, enunciaba, enunció, renuncié, renunciaron, anunciando, renuncies, anunciaste, denunciarnos, denunciaron, nuncio, denuncia, denunciarlos, denuncien, denunció, nuncios, renuncio, denuncia, denunciaría, anunciada, anunciado, renunciarse, anunciadas, anunciara, renuncie, anuncio, denunciarme, renuncias, anuncié, denuncia, denunciando, denunció, anunciar, renunciando, renunció, renunciado, denunciada, denunciado, denunciarlo, denunciarle, denunciadas, denunciarlo, denunció, renunciaría, anunciases, denunciara, anunciante, anuncian, renuncian, anunciadora, renunciad, denunciaron, anuncios, denunciar, renunciaba, anunciados, renunciarías, denunciaré, anunciase, denunciaba, renunciar, renunciaron, denuncias, denunciados, denunciando, anunciador, denunció, denunciadas, denuncia, denuncian, denuncie, renunciaban, anunciada, denunciaran, anuncian, anunciaban, denunciaban, denunciarme, anunciar, denunciado, denunciada, denunciaron, anunciarlo, anunciarnos, renunciara, renunciaré, anunciarle, denunciados, denunciaba, anunciarse, renunciarnos, anuncien, anunciarles

4. (73 words) confort, conformarnos, confortarle, confirmarse, confirmados, confirmarla, conformes, conforman, confortaban, conformemos, confortan, conformando, confortarlo, confirmar, confirmarlo, confirmadas, confirmaron, conformarme, confirmaban, conformen, conformaba, confirmaba, confirió, confirmaría, confirma, confirmó, conformarnos, confortador, confirmado, confirmada, conformase, confirmamos, conformasen, confortarse, confirman, confirmaros, conformaron, conformar, confirmarán, conformadas, conformaban, confirmarían, conformaste, confortado, conformaría, conformado, confirmarme, confortó, confirmas, confortaba, conformada, confortada, confirmé, confirmando, confortando, conformara, conformarlo, conformarla, conformaré, confortarla, confirmara, conformé, confirman, conforma, conformarse, confortables, conformamos, conformó, conforta, confirmase, confortable, confórmese, confirmarle

5. (64 words) discutió, discutidas, discuta, discutirlo, discute, diputada, disputar, discutí, discutidos, discuto, diskette, discutía, disputado, discurren, disputada, discutiré, discutamos, discutirse, discutida, disputarle, discuten, disputarla, disquetes, discutan, disputara, diputado, discutido, discutas, disputó, disquete, discorra, disputa, discurre, disputadas, dispute, disputaban, discutible, discutirle, discurría, discurtidor, disputen, disputas, diputados, discutimos, disputan, discutíamos, disutible, discurrir, discutir, disputando, discurríamos, discurtido, dispuso, disputados, discutías, dispuse, discurrían, disputarlo, discurtió, discutían, discutibles, diputadas, disputaba, disputarse

6. (57 words) subiéndose, subiéndole, viéndonos, sabiéndonos, sabiéndolo, viéndoos, abriéndome, habiéndote, viéndome, siéndoles, haciéndonos, asiéndolo, riéndoles, sabiéndome, riéndonos, viéndote, haciéndose, saliéndoles, viéndoles, viéndolas, abriéndonos, haciéndoles, riéndose, saliéndose, siéndome, haciéndola, haciéndole, sumiéndose, riéndome, haciéndolos, sabiéndose, viéndolos, habiéndole, abriéndoles, haciéndolo, habiéndolo, viéndose, asumiéndose, viéndola, viéndole, sabiéndola, abriéndolas, viéndolo, habiéndose, asiéndome, abriéndose, haciéndome, habiéndonos, haciéndote, valiéndose, haciéndolas, saliéndole, siéndonos, siéndole, abriéndole, asiéndonos, siéndolo

7. (56 words) exista, existía, exigían, existe, eximió, eximía, existí, exitosas, existo, eximidos, exigidas, exitoso, exquisitas, d'examen, exitosa, exit, exima, exilio, exime, exijo, exigió, eximí, exigía, exija, exige, exilios, sexista, existen, exigida, existido, exigido, exijan, eximio, exigidos, exigen, exijas, sexistas, éxitos, examen, eximir, existes, exitosos, exiló, exquisito, eximen, existió, eximido, existían, exilió, exquisita, éxito, exquisitos, exigimos, existir, existan, exigir

8. (56 words) tramitara, transmitir, transmutó, tramitar, tramitados, transmitían, transigen, transidos, transida, transmitidos, transitan, transité, transido, transmitan, transita, transmiten, transmitir las, transitó, transmitidos, transmitía, transmitirse, transmitió, transige, transmitidas, transmití, transit, transmito, transmita, transmite, tramiten, transmitido, tramitada, transmitirles, transmiten, transmitía, transmitirme, transiten, transmitida, tramitado, transmute, transmitirlo, transitar, transmuta, transmitir, transmitirle, transmitiré, transmitido, transmitir la, transidas, transmite, tramitando, tramitó, transmitidas, tramita, transmutar, tramité

9. (53 words) importaba, simporte, importar los, importada, importado, impartían, importantes, importarnos, impactan, importaban, importando, importados, importable, impartí, imparto, importarles, impostadas, imparta, imparte, impactó, importamos, importaría, importase, importar, importar le, importante, impartía, impartido, impartió, impartida, impartidas, impactar, importó, importants, importadas, importarte, impactos, importen, importarse, simportes, importan, importé, importa, importen, importa, impartir, impartidos, importara, impostado, impostada, importas, importador, importarme

10. (52 words) conservadors, conserjes, conservabas, conservara, conversor, conservadoras, conversar, conservarnos, conservadora, conversó, conversa, conservar las, converse, conservaban, conservasen, conserje, conservador, converger, conservar, conservarlo, conservarla, consérvame, conservando, conservé, conservarse, conserva, conserven, conservó, conversas, conservas, conservaran, conservamos, conservadas, conservemos, consérvese, conservaron, conversan, conversen, conservan, conservaba, conservarte, conservaría, conservados, conversos, conservarme, conservadores, conservada, conservase, convergen, conservar los, converge, conservado

English

1. (71 words) consuls, converts, congeal, conversed, consort, concedes, condoned, congealed, consigned, converse, consigns, convert, condones, concerns, converse, convert, consoles, converged, consign, consul, conceals, confines, conceit, conceive, consorts, confined, conceal, confines, confides, converge, concealed, confirm, concerned, conceits, console, concert, concurs, conceives, concurred, converts, confers, confounds, conserves, confound, confide, conserved, conforms, condign, conceived, confer, confine, consignor, concerts, congeals, concerts, concern, consoled, console, confirms, conferred, concede, concur, confirmed, consignors, conformed, consoles, concise, condone, conserve, conform, concert

2. (61 words) deception, dejection, direction, precession, inflection, infliction, retention, prevention, rejection, professions, dissension, reception, apprehension, election, recessions, procession, profession, infection, detention, elections, defections, detentions, reflections, injections, prehension, distension, receptions, injection, dissection, dissections, infections, dimension, inflictions, erections, ejection, refectations, reflection, detection, defection, processions, deflection, selections, apprehensions, inflections, distensions, dimensions, selection, deceptions, deflections, secession, pretensions, refectation, erection, recession, directions, rejections, precessions, secessions, dissensions, pretension, ejections

3. (47 words) rudeness, shrewdness, feminist, wordiness, fussiness, readiness, dowdiness, crustiness, wheeziness, mustiness, feminists, fustiness, seediness, mistiness, reediness, lustiness, seaminess, airworthiness, muzziness, rustiness, mugginess, roominess, rowdiness, reminiscent, moodiness, reminiscence, seemliness, reminisced, greasiness, redness, fuzziness, neediness, muskiness, phoniness, worthiness, greediness, ruddiness, speediness, queasiness, duskinness, muddiness, funniness, weediness, huskiness, reminisce, sunniness, easiness

4. (31 words) contest, confess, contend, congest, contain, condemned, consent, content, contained, condemns, confessed, contests, contents, contests, contexts, contender, contemned, contents, contemns, container, context, congests, contest, consents, contends, condemn, containers, contenders, content, contains, contemn

5. (29 words) sulkiness, leakiness, pearliness, bulkiness, oiliness, milkiness, pithiness, pokiness, chalkiness, bawdiness, earthiness, gawkiness, jerkiness, cheekiness, surliness, cheeriness, perkiness, curliness, luckiness, pawkiness, earliness, pluckiness, pickiness, chilliness, giddiness, silkiness, silliness, gaudiness, bulginess

6. (26 words) underlays, undersigned, underside, underlie, underlay, underlain, underpaid, underplay, underline, underhand, undersigns, undersized, underpays, underlies, undermines, undermanned, underplayed, underpay, undersign, undermine, undersize, underplays, undermined, underlined, underlines, undersides

7. (23 words) convictions, contentions, collections, connections, concessions, confections, correction, convection, conceptions, convention, concession, confection, contention, collection, conventions, confectioner, confessions, corrections, conception, confession, confectioners, connection, conviction

8. (23 words) Liberals, laterally, illiterates, illiterately, illiberal, illiterate, liberally, literacy, illiberally, Liberal, literates, littoral, laterals, illiteracies, lateral, literate, littorals, illiteracy, literally, liberalized, literary, literately, liberalize

9. (23 words) billionths, pinion, million, millionth, pillions, millions, millionaires, pinioned, millionaire, bullion, pinions, minion, pillion, billions, opinion, minions, millionths, billiards, bilious, billionth, billiard, billion, opinions

10. (21 words) destroyers, distraut, disobeyed, distrains, destroy, destroyed, destroyer, disobeys, disarrays, disarrayed, distraut, disobey, restrain, restraint, distraut, restrained, restrains, restraints, destroys, distraut, disarray

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