The unbounded productivity of (sign) language: Evidence from the Stroop task

Iris Berent[1]

Amanda Dupuis[1]

[1]Northeastern University

Address for correspondence:

Iris Berent
Department of Psychology
Northeastern University
i.berent@neu.edu
125 Nightingale
360 Huntington Ave
Boston MA 02115
Phone (617) 373 4033
Fax: (617) 373-8714

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Abstract

Unbounded productivity is a hallmark of linguistic competence. Here, we asked whether this capacity automatically applies to signs. Participants saw video-clips of novel signs in American Sign Language (ASL) produced by a signer whose body appeared in a monochromatic color, and they quickly identified the signs' color. The critical manipulation compared reduplicative (αα) signs to non-reduplicative (αβ) controls. Past research has shown that reduplication is frequent in ASL, and frequent structures elicit stronger Stroop interference. If signers automatically generalize the reduplication function, then αα signs should elicit stronger color-naming interference. Results showed no effect of reduplication for signs whose base (α) consisted of native ASL features (possibly, due to the similarity of α items to color names). Remarkably, signers were highly sensitive to reduplication when the base (α) included novel features. These results demonstrate that signers can freely extend their linguistic knowledge to novel forms, and they do so automatically. Unbounded productivity thus defines all languages, irrespective of input modality.

Introduction

Productivity is the hallmark of linguistic competence (Chomsky, 1957). Upon hearing *bagogo* and *malulu*, people extract the ABB pattern and they generalize it to *wufifi* (Berent & Shimron, 1997; Berent, Marcus, Shimron, & Gafos, 2002; Gervain, Macagno, Cogoi, Peña, & Mehler, 2008; Gervain, Berent, & Werker, 2012; Marcus, Vijayan, Bandi Rao, & Vishton, 1999). Speakers draw such phonological inferences rapidly and effortlessly, and they do so in a predictable, systematic fashion.

Phonological systems, however, are not limited to spoken languages. Like their spoken counterparts, every sign language exhibits phonological patterns (Brentari, 1998; Emmorey, Lane, Bellugi, & Klima, 2000; Sandler & Lillo-Martin, 2006; Stokoe, 1960), signers acquire their native phonology spontaneously (Petitto, Holowka, Sergio, & Ostry, 2001), and absent linguistic input, phonological systems emerge *de novo* (Brentari, Coppola, Mazzoni, & Goldin-Meadow, 2012; Sandler, Aronoff, Meir, & Padden, 2011). Nonetheless, sign languages heavily rely on iconicity (e.g., Sandler & Lillo-Martin, 2006; Thompson, Vinson, & Vigliocco, 2010; Thompson, Vinson, Woll, & Vigliocco, 2012), a feature that is arguably inconsistent with abstract combinatorial structure (for reasons we next detail). Accordingly, one wonders whether the capacity to freely extend phonological generalizations forms part of all languages, or of spoken systems, specifically. Furthermore, it is unclear whether such generalizations reflect only an off-line deliberate process, or whether generalizations apply automatically—without monitoring, and even in contrary to task demands (Tzelgov, 1997).

To address these questions, here we examine whether signers freely extend phonological generalizations even when they are asked to ignore the sign altogether— in a modified Stroop task. We begin by explaining the term "across the board generalizations" and relating it to the debate between competing accounts of mental architecture. We next outline the putative role of such generalizations in sign languages, and describe their evaluation in our current experiments.

The Scope Of Linguistic Generalizations

A large body of psycholinguistic research shows that people can readily extend the patterns observed in their language to novel forms. For example, upon hearing that *blixes are tridding*, native English speakers conclude that *blixes* are numerous individual entities, and that *tridding* is likely an action performed by those entities. The basis for such generalizations, however, is contentious.

The computational theory of mind (Fodor & Pylyshyn, 1988; Fodor, 1975; Marcus, 2001; Pinker & Prince, 1988; Pinker, 1997a, 1997b) has attributed these inferential capacities to powerful algebraic mechanisms that operate on structured linguistic representations. In this view, linguistic representations encode abstract categories (e.g., Noun). These categories are potentially open-ended (e.g., *dog, cat, …blix…*), and their members are all treated alike (e.g., *dog* is as good of a Noun as *blix*). Linguistic operations, in turn, manipulate the form of these abstract representations using abstract variables (e.g., X standing for any noun). Because operations over variables apply to entire classes, ignoring the distinctions between class members (e.g., the distinction between the familiar *dog* and the novel *blix*), linguistic knowledge can generalize ***across the board***, to any class member, familiar or novel. Accordingly, linguistic generalizations exhibit unbounded infinity

(Chomsky, 1957, 2005). The algebraic account, then, critically hinges on two assumptions: (a) the mind encodes open-ended categories that form **equivalence classes**; and (b) mental processes manipulate these classes by operating over variables. In what follows, we broadly refer to operations over variables as **rules**[1].

While rules are assumed (tacitly or explicitly) by many generative theories of language, their role has been the subject of an ongoing debate in cognitive science (Elman, 1993; Elman et al., 1996; Elman, 2005; McClelland & Patterson, 2002; McClelland, 2009; McClelland et al., 2010; Rumelhart & McClelland, 1986; Seidenberg & Jeffery, 1999). A large body of research has shown that, far from treating all category members alike, linguistic generalizations are exquisitely sensitive to the properties of specific category instances, including their familiarity, and the similarity to other known items (Albright & Hayes, 2003; Bybee & McClelland, 2005; Bybee, 2008; Frisch, Pierrehumbert, & Broe, 2004; Haskell, MacDonald, & Seidenberg, 2003; Pierrehumbert, 1993; Ramscar & Dye, 2011). Further challenges to this theory are presented by computational simulations that have claimed to capture human generalizations by ***associative*** systems—ones that eschew abstract categories and algebraic operations over variables (Bybee & McClelland, 2005; Elman et al., 1996; Flemming, 2001; McClelland & Patterson, 2002; McClelland et al., 2010; Oudeyer, 2001; Rumelhart & McClelland, 1986; Seidenberg & McClelland, 1989).

The debate currently centers on two issues. One question is ***computational***, namely, what computational mechanisms are necessary in order to adequately capture the linguistic generalizations evident in human behavior? Does a full account of linguistic generalizations require mechanisms that are innately equipped with algebraic rules, or is it possible to fully account for such generalizations by associative systems[2]?

A second question is ***empirical***—what is the *scope* of the linguistic generalizations that humans extend? The hallmark of an algebraic rule is that it applies to any member of a class—actual or potential. For example, the reduplication rule (α→αα) should apply to any α syllable, regardless of whether its phonemes are ***familiar*** (e.g., the native English phonemes */b/, /p/*) or ***novel*** (e.g., the fricative */x/* as in Chanukah). In what follows, we are going to refer to such generalizations as ***across-the-board generalizations***. Of interest is whether humans effectively extend their linguistic generalizations in this fashion, and whether they do so on-line, rapidly and automatically.

While this empirical question is clearly linked to the computational debate, the two questions are distinct. Finding that people generalize across the board, in a manner that is predicted by algebraic rules, does not mean that rules are necessary to capture such behavior. And indeed, several researchers have argued that such generalizations can emerge in computational mechanisms that lack rules (e.g., Eimas & Seidenberg, 1997; Joanisse & McClelland, 2015; McClelland & Patterson, 2002; Seidenberg, 1997; Westermann, 2016). Previous computational work (Berent, Wilson, Marcus, & Bemis, 2012; Marcus, 2001, 1998), however, suggests that across-the-board generalizations present a formidable challenge to various connectionist networks (e.g., simple recurrent networks and a feed forward networks) and the maximum entropy model of phonology (Hayes & Wilson, 2008). While these mechanisms successfully generalize the reduplication function to novel items with familiar features, they systematically fail to do so given items with novel features. For example, when presented with the training items *baba* and *papa*, both including the labial feature, these models would readily generalize to novel labial items (e.g., *mama*), but not to novel velar ones (e.g., *gaga*). We note that these computational assertions remain controversial (e.g., Joanisse & McClelland, 2015; Smolensky, Goldrick, & Mathis, 2014; Westermann, 2016). Our present research, however, does not directly address the computational debate (i.e., *how* people generalize their knowledge). Instead, our goal is to investigate the empirical question of *whether* people do in fact automatically extend linguistic knowledge across the board. By systematically exploring the scope of signed generalizations in on-line processing, we hope to lay the foundations for future computational investigations.

Gauging the Scope of Phonological Generalizations

Past research on spoken language has systematically explored the scope of linguistic generalizations by examining speakers' capacity to extend phonological and morphological generalizations to novel forms in both natural and artificial languages. For example, research with artificial language experiments has shown infants extend the reduplication rule ABB to novel ABB forms (Gervain et al., 2012; Marcus et al., 1999; Marcus, Fernandes, & Johnson, 2007; for similar results with signs, see Rabagliati, Senghas, Johnson, & Marcus, 2012), and such generalizations are evident even when the novel reduplicative forms exhibit novel features and phonemes (i.e., ones that did not appear in the familiarization items, Marcus et al., 1999).

Similar results obtain with natural languages. Like other Semitic languages, Hebrew allows identical consonants to occur at the right edge of the stem (i.e., βαα, e.g., *salal*, 'he paved'), but bans them in its beginning (i.e., ααβ, e.g., *lalas;* Greenberg, 1950; Leben, 1973; McCarthy, 1986, 1989). Past research has shown that Hebrew speakers freely generalize this restriction to novel Hebrew stems, resulting in a systematic dispreference of novel ααβ stems relative to either βαα or βα∂ controls (Berent & Shimron, 1997; Berent, Shimron, & Vaknin, 2001; Berent, 2002; Berent & Shimron, 2003; Berent, Vaknin, & Marcus, 2007). Remarkably, people extend the ban on ααβ, stems (relative to βαα controls) even when the reduplicative α consonant is unattested in Hebrew, and even when this consonant comprises of novel feature values (e.g., /θ/ in *thathak*, a consonant whose place of articulation is unattested in Hebrew, Berent et al., 2002). These empirical results are significant because they suggest that speakers can systematically extend the reduplication rule across the board.

In subsequent work, we asked whether such generalizations also form part of the linguistic competence of signers (Berent, Dupuis, & Brentari, 2014). Like many other sign languages, ASL uses reduplication in a variety of morpho-phonological functions (Wilbur, 1973; Wilbur, 2009). For example, reduplication is used to form disyllabic αα nouns (e.g., *seat*) from related monosyllabic α verbs (e.g., *to sit*, Supalla & Newport, 1978). Accordingly, disyllabic reduplicative signs αα are relatively frequent and well-formed, whereas nonreduplicative disyllables are far less frequent and arguably worse-formed. If signers extract the reduplicative pattern, they should thus favor reduplicative αα signs to nonreduplicative controls. In line with this possibility, we found that signers favor novel αα forms in forced choice rating, and they consider novel αα signs more sign-like in an on-line lexical decision task (Berent et al., 2014). Critically, these results obtained regardless of the familiarity with the reduplicative element. That is, people favored the reduplicative αα forms to the αβ control irrespective of whether the reduplicative form comprised of features that are all native to ASL, or whether its handshape feature is unattested at ASL (Berent et al., 2014).

The generalizations to novel (unattested) features cannot be explained by their phonetic assimilation to native ASL signs— the possibility that signers represent the novel handshape as an attested ASL handshape, akin to the tendency of Spanish speakers, for instance, to misperceive the English word /bɪ t/ as /bit/. If that were the case, then performance in the lexical decision task should have been unaffected by the feature composition of the novel signs (whether their handshape is native or unattested). But an inspection of the results shows this was not the case. Rather, lexical decision was significantly faster and more accurate in the presence of unattested features, suggesting that these features were in fact encoded as such. Remarkably, signers were able to represent the reduplicative structure of αα signs whose handshape feature was unattested

These findings from sign languages are particularly significant given their prevalent iconicity (Ormel, Knoors, Hermans, & Verhoeven, 2009; Thompson et al., 2010), which has been also shown to affect on-line processing by adults (Thompson, Vinson, & Vigliocco, 2009; Thompson et al., 2010), children (Ormel et al., 2009) and infants (Thompson et al., 2012, but see Bosworth & Emmorey, 2010; Emmorey et al., 2004; Caselli & Pyers, 2017). Because strictly iconic representations are analog, whereas rule-like generalizations might require representations that are algebraic and abstract (Fodor & Pylyshyn, 1988; Marcus, 2001; Pinker, 1997b), a purely iconic system would appear incapable of across-the-board generalizations. As such, sign languages present a particularly strong case for the algebraic account. The capacity of signers to freely generalize the reduplication function does not directly speak to the question of iconicity, but it does suggest that sign language can acquire representations that are discrete and abstract.

Together, these results suggest that speakers and signers can extend their phonological knowledge across the board—even to structures that are comprised of features that are unattested in their native language. In what follows, we subject these conclusions to a stronger test by asking whether across-the-board generalizations are evident in sign language ***automatically***, even when signers are instructed to ignore the signs altogether.

Do Signers Extend Phonological Generalizations Automatically?

To determine whether signers generalize their phonological knowledge automatically, the present investigation employs a modified Stroop task. In the original Stroop task (Stroop, 1935), participants are presented with words displayed in color (e.g., in blue), either ones that are congruent with the color (e.g., the word BLUE), incongruent (e.g., the word RED) or neutral (a series of letter strings, e.g., X's). Participants are asked to quickly name the color while ignoring the words' content. Results typically show an interference in responding to the incongruent- relative to the neutral condition. The Stroop-like interference is of interest because it gauges whether people extract linguistic information despite contrary task demands (Stroop, 1935; MacLeod & MacDonald, 2000; for review see MacLeod, 1991). Finding that people compute linguistic structure under such conditions would suggest that this computation is automatic, in the sense that it does not require active monitoring (Tzelgov, 1997).

Most existing research has used the Stroop task to examine whether people automatically access the meaning of color words (e.g. MacLeod, 1991). However, Stroop-like interference has also been used to gauge the computation of abstract linguistic structure, unrelated to color names (e.g. Berent & Marom, 2005; Berent, Pinker, Tzelgov, Bibi, & Goldfarb, 2005; Berent, Bibi, & Tzelgov, 2006; Dalrymple-Alford, 1972; Marom & Berent, 2010)—hereafter, we refer to these manipulations as a *modified* Stroop task. In one such study, Berent and colleagues (2006) examined whether Hebrew speakers automatically extract the abstract reduplicative structure of novel words, unrelated to color names. As noted above, Hebrew allows ABB stems (e.g., *salal*, 'he paved'), but bans AAB ones (e.g., *sasal*). Of interest is whether Hebrew speakers generalize the AAB ban to novel forms. To address this question, Berent and colleagues presented participants with novel Hebrew words, whose structure was either the ill-formed AAB (e.g., *sasam*) or well-formed ABB structure (e.g., *samam*). These printed words were presented in color, and participants were asked to name the color while ignoring the word. If people extract the AAB structure automatically, then the well-formed ABB structure should differentially affect the allocation of attention to the color naming task compared to the ill-formed AAB forms. Berent et al. noted that the direction of this effect (facilitation or inhibition) could not be predicted *a priori.* Indeed, it is conceivable that ill-formed (AAB) structures could either increase attention demands (due to the difficulty in the computation of ill-formed structure) or disengage attention, as ill-formed structures might be easier to ignore. The critical question, thus, is whether AAB forms differentially affect color naming relative to well-formed structures (ABB/ABC). Results from two experiments yielded such a differential effect. Specifically, well-formed (ABB and ABC forms) increased color naming latency to a greater extent than the ill-formed AAB forms, suggesting that well-formed structures are harder to ignore[3].

These findings demonstrate that speakers can automatically generalize their knowledge to novel forms. However, it is unclear whether such generalizations apply to sign languages. Several previous studies have shown that signers automatically access the lexicon in Stroop-like tasks. For example, Thompson and colleagues (2010) have shown that signers access the meaning of signs when the task only requires that they judge the shape of the signer's fingers. Other results suggest that signers automatically access the sign's meaning in picture naming tasks (Baus, Gutiérrez-Sigut, Quer, & Carreiras, 2008; Baus, Gutiérrez, & Carreiras, 2014; Corina & Knapp, 2006; Hildebrandt & Corina, 2002). Finally, signers also automatically activate color names in a Stroop task. In a pioneering study, Marschark and Shroyer (1993) have reported that incongruence between still images of signs and their colors interferes with color naming, and subsequent research (Dupuis & Berent, 2015) has demonstrated this interference with video clips of dynamic signs. Together, these findings establish that signers can automatically extract the internal lexical properties of signs. However, these results leave open the question of whether signers can also automatically generalize the sign's abstract structure.

To determine whether signers extend phonological rules automatically, here, we use an adaptation of the Stroop paradigm. Participants in our experiments—deaf signers of ASL—are presented with short video clips of ASL-like signs, where the signers' body (the torso, arms and hands) is edited to appear in a monochromatic color. They are asked to rapidly sign the color of the sign while ignoring its contents.

In the critical manipulation, the video clips feature novel ASL signs, unrelated to color terms—either ones with reduplicative αα structure (where α stands for any syllable) or nonreduplicative controls consisting of two distinct syllables (αβ). Half of the αα-αβ pairs were comprised of handshapes that are all ***native*** to ASL; the other half included handshapes with a single feature that differs from a native ASL handshape, resulting in handshapes that do not exist in ASL, but are possible in other sign languages ("EE[4]", from the Russian Sign Language; "P", from the Chilean Sign Language; and "H", from the Portuguese Sign Language)--hereafter, ***nonnative*** features; see Appendix B.

Our research addresses two questions: (a) will novel αα signs differentially affect color naming relative to αβ controls; and (b) will this effect of reduplication extend even to signs with nonnative features. We outline the predictions concerning each of these questions in turn.

Consider first the effect of reduplication on color naming. Given that αα structures are preferred (i.e., better-formed and more frequent) in ASL relative to αβ forms (Berent et al., 2014), and given that our past Stroop research (Berent et al., 2006) has shown that worse-formed structures are easier to ignore, we expect signers to ignore αβ syllables more easily than the better-formed reduplicative forms, resulting in a reduced interference in color naming. Restating this prediction with respect to reduplicative forms (the focus of our investigation), we expect αα disyllables to interfere with color to a greater extent than their αβ controls.

Our critical question concerns the ***scope*** of the reduplication effect. If the αα preference only reflects the statistical co-occurrence of specific phonological elements (e.g., the possibility that the two A handshapes in the AA disyllable co-occur together more frequently relative to those in AD signs), then the reduplication effect should only obtain for signs with native features; nonnative αα signs include two unfamiliar handshapes, so these stimuli are no more frequent, hence, no more likely to interfere with color naming relative to αβ controls. In contrast, if speakers can generalize their phonological knowledge across the board, then they should be able to extract the reduplicative structure irrespective of the familiarity with the signs' features—for both native and nonnative αα signs. Nonetheless, the effect of reduplication on *color naming* could differ for native and nonnative features

To appreciate these differences, it is critical to note that the ASL color names used in these experiments are all reduplicative, and they are quite similar to the native αα signs. In fact, our novel native αα signs differ from color signs by a single parameter, i.e., the handshape, and the similarity of these novel signs to color names could elicit a strategic response that might attenuate their effect.

To illustrate this phenomenon, let us consider an analogy from English. Consider a modified Stroop task, featuring novel words like *kreen,* and *xreen*—words that differ from color names (*green*) by a single feature (e.g., voicing, manner of articulation)[5]. When this distinctive phonological element is ***non-native*** to the language (for words like *xreen*, derived from *green*), the contrast with the color name might be quite salient, so the perceived conflict with color names is minimal. But when the words are compared of elements that are all ***native*** to the language (e.g., *kreen*), the similarity to color names (e.g., green) is far less salient, and consequently, the interference to incongruent colors (e.g., "red") should increase. To protect against the increased interference from native features, participants might need to strategically control their performance by means of deliberate control (either by increasing their monitoring of color naming, or by inhibiting the processing of words; for details, see section 4.2).

Extending this line of reasoning to our sign language manipulation, we expect novel signs with native features to be more similar to color names than those with nonnative features. And since, by definition, these novel signs are incongruent with the color name, we expect the inclusion of αα native signs to effectively increase the perceived incongruence (i.e., information conflict) between the color and the signs.

Past research on the word-color Stroop interference has shown that increasing the proportion of incongruent trials attenuates the Stroop interference due to top-down control of color naming (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001, for review). Our past Hebrew results suggest that such control can be further elicited by novel stimuli that are similar to color words (Berent et al., 2006). In these experiments, novel forms (AAB, ABB ABC) were presented various morphological patterns. One pattern was unaffixed (e.g., *sasam, samam*, for AAB vs. ABB), and thus, similar to the surface form of Hebrew color names (e.g., *sagol*, "purple"). In another condition, the same AAB/ABB forms were heavily affixed, and thus, radically different from color names (e.g., *histasamtem* vs. *histamamtem*, from the stems *sasam* vs. *samam*). Results showed that reduplication reliably modulated color naming when the words were heavily affixed, and dissimilar to color words (e.g., *histasamtem*, from the stem *sasam*). In contrast, no sensitivity to root structure obtained for unaffixed words (e.g., *sasam*)—those whose structure is similar to color names. The null effect for the unaffixed words is specific to the Stroop task, as these stimuli typically yield stronger effects of reduplication when the stimulus is attended (in lexical decision, see Berent et al., 2001; Berent, Vaknin, & Shimron, 2004). Accordingly, the attenuated effect of reduplication for unaffixed words is likely due to regulatory control that attenuated the processing of color naming.

Concerning our present manipulation, we thus predict that the perceived incongruence of the native αα signs with color naming will prompt signers to strategically regulate color naming in their presence. By contrast, nonnative reduplicative signs are sufficiently dissimilar to color names, and consequently, these trials will be spared this strategic inhibition. So while we fully expect signers to extract the reduplicative structure of *all* novel signs, the effect of reduplication on color naming will vary for native and nonnative signs. Critically, we predict that the effect of reduplication will be *stronger* for signs with nonnative features compared to novel signs whose features are native to ASL—a pattern ***opposite*** to the one predicted by the statistical account.

As a manipulation check, our experiments also included a third group of items that correspond to ASL color signs. In a recent study, we have shown that ASL color signs can elicit the Stroop interference (Dupuis & Berent, 2015). But given the paucity of research on the Stroop interference with signs, we sought to replicate this finding and in so doing, ensure that color naming is sensitive to the internal properties of the signs. Accordingly, we compared color naming to three types of signs—ones that are congruent with their color (e.g., the sign for *blue* displayed in a blue color), incongruent (the sign for *blue* presented in yellow), or neutral (the novel sign with two identical syllables). If signers automatically encode the internal structure of the sign, then we expect incongruent signs to interfere with color naming relative to the neutral condition. In addition, we expect the congruent condition to facilitate color naming relative to neutral signs.

Summarizing then, our two experiments each include two manipulations. Our control manipulation examined the color-sign interference, using existing ASL color signs. Our primary manipulation examined the effect of reduplication on novel signs, unrelated to color—either ones with native features or with features that are nonnative to ASL. Native and nonnative signs were presented in distinct blocks of trials, as we were concerned that the encounter with nonnative features might contaminate responses to signs with native features, presented in adjacent trials (e.g., encourage participants to ignore all signs, resulting in the elimination of the color-sign interference). We administered these manipulations (experimental and control) in two experiments. In each experiment, the color signs were mixed with the reduplicative signs and their controls. The two experiments differed primarily on the order of presentation of the native and nonnative signs. Experiment 1 first featured first a block of signs with native features followed by a block of signs with nonnative features; Experiment 2 presented the two types stimuli in a counterbalanced block order.

Experiment 1

Methods

Participants

Twelve participants took part in the experiment. They were all Deaf signers who were fluent in ASL, and they acquired ASL prior to age six. Of these, one participant had obtained a high school degree, one an Associates Degree, five had or were pursuing Bachelors degrees at the time of testing, and five had or were pursuing a Masters Degree. One participant had Deaf parents; one had older Deaf siblings. The study was approved by the IRB of Northeatsern University. Written informed consent was obtained from all participants.

Materials

Stimuli were ASL-like signs, edited such that the signers' body (the torso, from the waist up, the arms and the hands) appeared in a monochromatic primary color—either blue, green, or yellow. We selected these colors because past research has shown that the common color names associated with primary colors (e.g., *blue*) yield a stronger Stroop interference compared to the less common color words associated with non-primary colors (e.g., *scarlet*, e.g., Proctor, 1978). All signs were produced by the same female signer who is fluent in ASL and they measured 9" height x 15" width. To ensure that the uniform coloring of signer's hands, the signer further recorded the signs wearing gloves. To control the duration of the two syllables, the signer articulated all signs (color names and novel) to the beat of a metronome. The materials consisted of two sets, corresponding to our two manipulations—reduplication, and color-sign interference.

Reduplication materials.

The reduplication materials featured novel ASL signs. All signs were disyllabic, and they were either reduplicative (αα) or matched non-reduplicative controls (αβ). Reduplicative and nonreduplicative signs invariably shared the phonological parameters of location, palm-orientation, and movement with ASL color signs (the same signs used in the *Color-*

sign interference manipulation) and differed from color signs only in their handshape. For example, like the color signs (BLUE, GREEN, and YELLOW), all novel signs were signed in neutral space (location), with an outward facing palm (palm-orientation), and had two wrist flicks (movement). The contrast in handshape was designed to equate the αα and αβ signs for morphological structure. Recall that reduplication is a morphological operation in ASL, and consequently, our novel αα signs could be represented as bimorphemic[6]. To equate αα and αβ for morphological structure, it was thus necessary to design the αβ forms so that they are likewise parsed as bimorphemic. To this end, we relied on the fact that most ASL stems have a single set of "active" (or selected) fingers, as well as location (Brentari, 1998; Liddell & Johnson, 1986; Sandler & Lillo-Martin, 2006). Accordingly, signs with two groups of active fingers are likely to be perceived as bimorphemic, and our past experimentally research has shown that signers are sensitive to this constraint (Berent, Dupuis, & Brentari, 2013). The handshape contrast between the α and β syllables of the αβ signs was designed to equate the αα and αβ signs for their perceived morphological structure.

There were two subsets of reduplicative signs. In the native reduplicative signs, αα and αβ had a handshape that is native to ASL (native reduplicative signs), whereas in the nonnative reduplicative signs, the handshapes in each of the α syllable were nonnative to ASL.

a. *Native reduplicative materials*. The native reduplicative materials comprised of three pairs of novel signs (αα and αβ), whose phonological features were all native to ASL. In what follows, we will express the structure of these signs by their handshape—either the -A-, -C- or -D- ASL handshape. The native reduplicative signs (αα) were comprised of AA, CC, and DD combinations. Their matched nonreduplicative controls (αβ) were formed by combining the first syllable of a reduplicative novel sign with the second syllable of another (e.g., αα + ββ → αβ, βα). To give an English example, our manipulation would be analogous to using the disyllabic words *papa* and *mama* to yield *pama* or *mapa*. Thus, possible nonreduplicative signs were AC, AD, CA, CD, DA, and DC; but to match these to the reduplicative novel signs, only three were used (AD was paired with AA; CA with CC; and DC with DD).

b. *Non-native reduplicative signs*. Nonnative signs likewise comprised of three matched pairs of novel signs (αα and αβ disyllables). Their structure was similar to the native signs with the exception that each syllable was comprised of a handshape that was nonnative to ASL—either the Russian Sign Language "EE", the Chilean Sign Language "P", or the Portuguese Sign Language "H" (see Appendix B). Critically, these handshapes are sufficiently distinct from ASL handshapes, so they are unlikely to be mistaken for a native ASL feature. Using the numbers 1, 2 and 3 to refer to the three handshapes, the structure of the reduplicative nonnative signs can be described as 11, 22, and 33. Nonreduplicative nonnative signs comprised of 12, 13, 21, 23, 31, and 32 combinations, divided into two lists (List A – 12, 23, and 31; List B – 13, 21, and 32), counterbalanced such that each participant only saw one list. The complete set of native and nonnative items is presented in Appendix A. The video-clips of the native and nonnative signs (in the color yellow) can be viewed by vising https://www.youtube.com/playlist?list=PLBdp4mOe9SrcvkAYqF5skFgoCZnJU1O5F

Color-sign interference materials.

This manipulation included the ASL color signs BLUE, GREEN, and YELLOW. The neutral condition consisted of a novel reduplicative sign (XX), that matched the location, movement, and palm-orientation of the color signs (as well as those of the novel signs used in the *reduplication* manipulation), and differed from color signs only in handshape (the native ASL handshape X)[7]. Items were presented as congruent (e.g. the sign BLUE in the color blue), incongruent (e.g. the sign GREEN in the color blue), or neutral (i.e., the neutral novel sign XX in any color). Each sign appeared with equal frequency in each of the three colors.

The experimental materials were divided into two blocks. The first block featured half of the items in the color-sign interference manipulation (72 trials per block) along with the reduplication manipulation with native signs (2 αα/αβ x 3 pairs X 3 repetitions x 3 colors=54 trials); the second block featured the second half of the color-sign interference items (72 trials) along with the reduplication manipulation with non-native signs (2 αα/αβ x 3 pairs X 3 repetitions x 3 colors=54 trials). In what follows, we thus denote the block by the reduplication manipulation. The block of trials including the native signs is denoted the "native block", whereas the one with nonnative signs is denoted the "non-native block". The composition of the items presented in the two blocks is detailed in Table 1.

Table 1 about here

Procedure

Participants were seated near a lab computer in a quiet room. Each trial began with "get ready" screen presented for 500 ms, including a fixation point (+) and below it, the trial number. The fixation point was followed by a single video of the signer producing one stimulus item (e.g., the sign BLUE presented in the color green). Participants were asked to sign the color of the video (blue, green, or yellow) as quickly and accurately as possible. The presentation of the video clip was immediately replaced by the "get ready" screen for the next trial.

Response time and accuracy were coded on-line by an ASL-fluent experimenter (by selecting one of three keys, corresponding to the participant's response), and the experimenter's coding automatically triggered the next trial. The experimenter was blind to the experimental conditions, as she was unable to view the computer screen. We note that this on-line coding procedure limited the sensitivity of our manipulation to participants' *absolute* response time at any given trial. Our main interest is in the comparison of our experimental conditions (e.g., αα vs. αβ signs) *across* trials. Given that experimenter was entirely blind to the content of the trial, the on-line coding could not have confounded the sensitivity of our procedure to the manipulation of interest.

The instructions to experiment were given in ASL, pre-recorded by a native ASL signer. Prior to each of the two experimental blocks, participants were presented with a practice sessions consisting of 15 trials (9 color-sign interference trials and 6 reduplication trials), which provided feedback on their accuracy (using pre-recorded ASL messages, indicating both "correct responses" and "errors"). No practice was given during the experimental session.

Results and Discussion

In Experiments 1-2, response time analyses were conducted over correct trials only. Response time outliers were calculated separately for the color-sign and reduplication conditions; outliers were defined as correct responses falling 2.5 standard deviations beyond the mean or faster than 200 ms (less than 3% of responses). All statistical analyses were conducted using participants as the random variable. Because the color-sign and reduplication conditions were each based on only three items (three color signs, three pairs of attested reduplication signs for the attested and unattested conditions), we did not conduct statistical analyses over items. Response time in all experiments is measured from the onset of the sign.

Due to an error in editing the stimuli, one of the color-interference items in Experiment 1 (the neutral novel sign XX in the color blue) was distorted (the color of the signer's torso was ambiguous), and consequently, it was excluded from the analyses of the color-sign interference. Accordingly, the analyses of the color-sign interference were based on the data from two colors (green and yellow), whereas the reduplication manipulation data included all three colors.

The Color-Sign Interference

Figure 1 presents the effect of sign-color congruence on response time and errors. An inspection of the means suggests that participants were sensitive to the congruence between color signs and their colors, such that incongruent signs (e.g., the sign for *green* in yellow) elicited slower responses relative to the neutral condition.

Figure 1 about here

In line with this conclusion, a 2 Color (green/yellow) x 3 Congruence (Congruent/Neutral/Incongruent) ANOVA conducted on response time yielded a reliable effect of congruence ($F(2, 22)=4.41$, $MSE = 1031$, $p < 0.03$). Congruence did not reliably modulate the error rate ($F(2, 22)=1.59$, $MSE=.021$, $p<.23$). No other effects were significant (all $F<1$).

Planned comparisons showed that color naming latency to the congruent condition did not differ from the neutral condition ($t<1$). In contrast, incongruent items elicited slower responses than neutral items ($t(22)=2.48$, $p<.03$).

These results replicate the Stroop interference, reported in our previous research (Dupuis & Berent, 2015), suggesting that signers automatically activate the meaning of arbitrary color signs. Given that participants in the Stroop task are sensitive to the meaning of signs, we can proceed to ask whether they also extract their abstract structure, namely, reduplication.

The Reduplication Effect

Figure 2 depicts the effect of reduplication on color naming latency. An inspection of the means suggests that reduplication did not affect responses to signs with native features. Remarkably, reduplication modulated color naming in the presence of signs with nonnative features. Specifically, reduplicative signs with nonnative handshapes elicited slower responses compared to nonreduplicative controls.

Figure 2 about here

These conclusions were supported by the results of the statistical analysis. We examined effect of reduplication using 2 Reduplication (reduplicative/nonreduplicative) x 3 Color (blue/green/yellow) ANOVAs, conducted separately on response time to the signs with native and nonnative features. Because accuracy to several of the color conditions was at ceiling (with no variance), the effect of reduplication on response accuracy was assessed across colors by matched t-tests performed separately for native and nonnative signs (with the errors arcsine transformed).

The analyses of native signs yielded no reliable effects (all $F<1$; $t<1$). In contrast, the analysis of nonnative signs yielded a significant effect of Reduplication ($F(1, 11)=5.07$, $MSE=3254$, $p<.05$), as reduplicative signs with nonnative handshapes elicited slower responses compared to non-reduplicative controls[8]. No other effects were significant in either response time (all $F<1$) or errors ($t<1$).

Table 2 about here

Summarizing, the finding from nonnative signs suggest that signers are sensitive to the internal reduplicative structure of signs. Reduplicative signs (αα) with nonnative handshapes elicited slower color naming than αβ nonreduplicative controls. In contrast, no effect of reduplication obtained for signs with native features. We suggest that this null effect is due to the similarity of native reduplicative signs to color names in ASL. Before we further consider this explanation, however, we must first rule out the possibility that the differences between native and nonnative signs are only due to their block order (i.e., the fact that nonnative signs were invariably presented in the second block of trials). To this end, Experiment 2 seeks to replicate the findings while controlling for the block order of native and nonnative signs.

Experiment 2

Experiment 2 reevaluated the effect of reduplication for native and nonnative signs. To control for the effect of block order, native and nonnative signs were presented in distinct blocks whose order was counterbalanced across participants. Thus, each block of trials featured a mixture of the novel αα and αβ signs (either native or nonnative) along with the color signs (congruent, incongruent and neutral).

To further ensure that participants attend to the signer's hands, we also cropped the video clips from Experiment 1 so that they only displayed the upper body of the signer (from the middle of the signers' torso and up). This modification was designed to counter the possibility that participants could avert attention to the sign by attending to areas of the body that are linguistically irrelevant, and in so doing, eliminate the effect of the sign's reduplicative structure on color naming.

Our main question is whether participants are sensitive to the reduplicative structure of signs—both native and nonnative signs. As a methodological check, we also assess the color-sign interference (i.e., the Stroop effect) in the two groups of trials.

Methods

Participants

Twelve participants took part in this experiment. Participants were Deaf signers who were fluent in ASL. All participants acquired a sign language prior to age seven; eight first acquired ASL, whereas four acquired SEE (Signed Exact English - an ASL/English hybrid that employs ASL signs in English word order) by age five and later acquired ASL. At the time of testing, all participants were using ASL as their primary language. Of these, two had completed high school degrees, three had Associates Degrees, three were pursing or completed Bachelors degrees, three were pursing or completed Masters Degrees, and one was pursuing a PhD. One participant has Deaf parents. Two subjects also participated in Experiment 1; the two testing sessions were separated by nearly two years.

Materials and Procedure

The stimuli consisted of the same video clips used in Experiment 1. To discourage participants from averting their gaze away from the singer's hands, these videos were edited in iMovie such that the signer only appeared from the middle of the torso up. Each sign measured 5" (height) x 9.5" (width). The procedure was otherwise as in Experiment 1. Signers' responses in Experiments 1-2 were coded by the same experimenter.

Results and discussion

The Color-Sign Interference

Figure 3 plots the effect of sign-color congruence on color naming latency and accuracy. An inspection of the means suggests that participants were sensitive to the internal structure of the signs, as incongruent signs yielded slower and less accurate responses compared to the neutral condition.

We next assessed the effect of congruence by means of a 3 Congruence x 3 Color ANOVAs of response time. Because response accuracy to several of the colors was at ceiling (with no variance), the error analysis assessed the effect of congruence across colors using a one-way ANOVA (errors were arcsine transformed). The effect of congruence was significant in both response time (F(2,22)=8.83, MSE=2576, p<.0002) and errors (F(2,22)=6.92, MSE=.023, p<.005).

Figure 3 about here

Planned contrasts showed that color naming in the incongruent condition was reliably slower (t(22)=2.79, p<.02) and less accurate (t(22)=3.51, p<.002) relative to the neutral condition. Responses to the congruent and neutral conditions did not differ reliably (t<1.35, for response time and accuracy).

The Reduplication Effect

Figure 4 presents the effect of reduplication on responses to native and nonnative signs. An inspection of the means suggests that reduplicative signs with nonnative features impaired color naming accuracy. In contrast, native signs yielded no effect of reduplication.

Figure 4 about here

We assessed the effect of reduplication by means of 2 Reduplication x 3 Color ANOVAs on response time and errors (arcsine transformed), conducted for signs with native and nonnative features.

The analyses of native signs yielded no reliable effect of Reduplication (F<1 in both response time and errors), Color (F(1,22)=1.75, MSE=2169, p<.20; F(1,22)=1.43, MSE=.025, p<.26; In response time and errors), or a Color X Reduplication interaction (F(1,22)=1.69, MSE=1150, p<.21 F(1,22)=1.13, MSE=.038, p<.34, in response time and errors).

By contrast, the error analysis of responses to nonnative signs yielded a reliable effect of Reduplication (F(1,11)=6.80, MSE=.025, p<.03)[9]. No other effects were significant in the error analysis (all F<1). Similarly, no significant effects were found in response time to nonnative signs (all p>.15)

Table 3 about here

Summarizing, the results of Experiment 2 converge with those of Experiment 1 to suggest that the effect of reduplication on color naming is selective to nonnative signs. We next turn to explain these findings and address their broader significance.

General Discussion

This research examines whether signers automatically generalize their linguistic knowledge across the board. To address this question, we gauged the effect of reduplication on color naming. We reasoned that reduplicative signs are preferred to nonreduplicative controls, as they are better formed and more frequent in ASL and other sign languages (Berent et al., 2014; Supalla & Newport, 1978; Wilbur, 2009). Accordingly, if signers automatically extract the reduplicative structure, then novel reduplicative signs should be harder to ignore, hence, they should interfere with color naming relative to matched non-reduplicative controls. Of interest is whether signers can extract the reduplicative structure of signs even when these items include phonological features that are nonnative to ASL.

Results showed that color naming was impaired in the presence of nonnative reduplicative signs, and this effect obtained in both Experiment 1 (in response time) and Experiment 2 (in accuracy). However, no effect of reduplication was found for native signs.

We suggest that the null effect of reduplication with native signs is due to their similarity to ASL color signs. Before further discussing the results with native signs, however, we would like to ensure that the reduplication cost with their *nonnative* items is not due to extraneous reasons, unrelated to their reduplicative structure. Having shown that participants do in fact extract the reduplicative structure of nonnative signs, we next consider why this effect is absent with native signs. We conclude by evaluating the implications of the results for competing accounts of mental architecture.

The Origins of The Reduplication Cost for Nonnative Signs

The finding that the reduplicative effect was confined to nonnative signs naturally leads one to worry that these costs might reflect extraneous reasons, unrelated to reduplication. Note that feature novelty cannot, in and of itself explain the reduplication effect for nonnative signs, as the αα signs and non-reduplicated αβ counterparts each comprised of two non-native features. However, it is possible that the reduplication cost is due to nonlinguistic visual artifacts that render nonnative reduplicative signs harder to process. Recall, however, that all signs were matched for the duration of their two syllables by having the signer who produced them follow the rhythm of a metronome. Accordingly, it is unlikely that the reduplicative cost is due to the dysfluency of αα signs. To further demonstrate that the reduplication cost with nonnative signs is not due to general perceptual/fluency artifacts, we administered the manipulations in Experiments 1-2 to two groups of English speakers who had no knowledge of ASL (N=12 participants per group). We reasoned that any costs associated with perceptual artifacts should emerge irrespective of knowledge of ASL—for signers and nonsigners alike. However, no such cost obtained for English speakers (see Table 4).

Table 4 about here

Given that the cost for nonnative αα signs cannot be attributed to either feature novelty or perceptual artifacts, the most likely explanation for the reduplication cost is reduplication itself. This conclusion agrees with our past finding that signers favor novel reduplicative forms to nonreduplicative controls, a result obtained in both rating and on-line lexical decision (Berent et al., 2014). Because reduplicative signs are preferred, they may be harder to ignore, and consequently, reduplicative signs interfere with color naming to a greater extent. This explanation is also in line with our past research in Hebrew (Berent et al., 2006). Recall that Hebrew allows ABB stems (e.g., *simum*), but not AAB ones (e.g., *sisum*). Using a modified Stroop procedure, we found that novel ABB stems (unrelated to color names) interfere with color naming to a greater than matched ill-formed controls (AAB stems). These results suggest that participants automatically extract the abstract reduplicative structure of novel linguistic forms that are unrelated to colors names, and that better-formed structures interfere with color naming to a greater extent than their ill-formed counterparts.

Why Are Signers Indifferent to the Reduplication of Native Signs?

Given that participants in our experiments were sensitive to the reduplicative structure of nonnative signs, we now turn to consider why this effect was absent with native signs. The answer, we suggest, lies in the similarity of native signs to color names in ASL. Like our native signs, the ASL names of the color used in our experiments, and they differ from our novel signs by a single feature parameter of the handshape. When this feature parameter consisted of a handshape that is nonnative to ASL, the distinction was sufficiently salient to clearly differentiate these stimuli from color names. In contrast, native reduplicative signs are highly similar to color names. And since, by definition, novel signs are incongruent with the color name, their presence effectively increased the overall level of color-sign incongruence. The competition might have prompted participants to strategically control the color naming response.

This possibility is consistent with two lines of evidence. One comes from the above-mentioned research on the effect of Hebrew reduplication on color naming. Results showed that people were highly sensitive to the reduplicative structure of stems that were heavily affixed (e.g., *histasamti*, from the stem *sasam*). Remarkably, no effect of reduplication obtained for unaffixed stem (e.g., *sasam*), even though these stems typically yield far stronger effects in reading tasks (e.g., lexical decision, Berent et al., 2001). We suggest that the null effect of reduplication for unaffixed words is due to strategic control, prompted by the similarity of those items to color names, which are likewise unaffixed.

There is also ample evidence for strategic control in the Stroop task itself. For example, participants are known to modulate performance in the Stroop task depending on the level of response competition and the constitution of the items (Botvinick et al., 2001). A high proportion of incongruent color words attenuates the cost of the color-word interference (e.g., Entel, Tzelgov, Bereby-Meyer, & Shahar, 2015; Logan, 1980; Tzelgov, Henik, & Berger, 1992). In fact, participants have been shown to strategically adjust their color naming response by tracking the contingency between the experimental stimuli and their color on an item-by-item basis (e.g., Jacoby, Lindsay, & Hessels, 2003), even when the stimulus is unrelated to color (i.e., for geometric shapes, Levin & Tzelgov, 2016). We suggest that the similarity of reduplicative native signs to color names triggers similar control strategies in our experiment.

To evaluate this possibility, we next examined whether the constitution of novel signs (native vs. nonnative) affected responses to ASL color signs. We reasoned that, if the insensitivity to native αα signs reflects strategic adjustment, then this adjustment could also modulate response to ASL color signs in the same block of trials. In line with past research, we predict that the enhancement of the color-sign competition (due to the presence of native αα signs) should attenuate the Stroop incongruence effect (i.e., the cost incurred by the incongruent relative to the neutral condition should be smaller in the presence of native- relative to nonnative signs). To the extent that the presence of native (color-similar) signs also prompts signers to control the processing of the signs, then the native condition could also enhance the congruence effect (i.e., the advantage of the congruent relative to the neutral condition). We thus turned to compare the effects of color-sign incongruence (i.e., responses to the incongruent relative to the neutral condition) and color-sign congruence (i.e., responses to the neutral relative to the congruent condition) on the presence of native and nonnative signs.

Figure 5 about here

Figure 5 plots the effect of novel sign composition (i.e., native vs. nonnative signs) on the color-sign congruence effect in response time. An inspection of means suggests that the incongruence effect was attenuated in the presence of native signs compared to nonnative signs. Statistical tests using planned comparisons (see Table 5) found this effect significant in Experiment 1 only with nonnative signs; no significant effects obtained with native signs. Similarly, in Experiment 2, the incongruence effect with native signs (Δ=22 ms) was half the size of the effect with nonnative signs (Δ=44 ms), and it was only marginally significant.

The congruence effect showed the opposite pattern. Here, the advantage of congruent signs was numerically larger in the presence of native signs, and this advantage was found statistically significant with the native signs in Experiment 2 (Δ=29 ms), but not with nonnative signs (Δ=4 ms, see Table 5).

Table 5 about here

These results confirm that native and nonnative signs elicit strategic control whose effect is not specific to reduplication. The precise nature of those strategies is not entirely clear from our present findings. One possibility is that participants attempted to minimize the color-sign conflict by allocating attention to the color naming task (Botvinick et al., 2001). In this view, participants monitored the conflict between the color naming task and the sign. When a high level of conflict was detected (i.e., in the presence of reduplicative native signs), participants enhanced their attention to color naming, and consequently, the effects of sign structure (i.e., reduplication) and meaning (i.e., the color-sign interference) were minimized. Note that this account leaves open the possibility that signers invariably extracted ***all*** aspects of native signs, including their reduplicative structure—strategic control, in this view, only affected the potential for the sign to ***interfere*** with color naming, not its processing per se. This framework explains why native reduplicative signs (which are similar to color names) resulted in both (a) no effect of reduplication (with novel signs); and (b) a weaker effect of color-sign incongruent (for color signs). However, this proposal does not explain why the allocation of attention to color naming enhanced the color-sign congruence effect in Experiment 2.

An alternative account asserts that the strategic adjustment further modulated sign processing. In this view, participants monitored for color-sign incongruence, and adjusted sign processing on a trial-by-trial basis (e.g. Jacoby et al., 2003). A high level of incongruence (i.e., with native signs) would momentarily decrease the allocation of attention to the sign, whereas its absence (with nonnative signs) would maintain, or even encourage sign processing. Since color signs are more familiar than the novel reduplicative materials, they might have been more resilient to suppression than the novel native signs, presented at the same block of trials. This account would explain why the presence of native signs resulted in congruence effect (for color signs) but no reduplication effect (for novel signs).

The critical question, for our present purposes, is whether such adjustment specifically affected the extraction of reduplication. Given that all conditions were sensitive to the color-sign incongruence (see Table 5), it is clear that signers did not abolish sign processing altogether. But whether participants continued to extract the reduplicative structure is uncertain—the results from native signs do not speak to this question. Accordingly, we cannot determine whether signers invariably extract the sign's constituent structure fully, or whether sign processing (including the processing of reduplication) can be partly suppressed.

While we cannot rule out the possibility that signers can occasionally halt the generalization of linguistic principles, our results make it clear that participants need not engage in deliberate controlled processing in order for them to extract the constituent structure of signs. And indeed, nonnative signs yielded robust effect of reduplication, even though these stimuli are markedly distinct from color signs (i.e., in the absence of any incentive to process their structure), and despite the fact that their reduplicative structure interfered with color naming. Accordingly, even if signers can strategically suppress the generalization of linguistic knowledge under certain conditions, such control is clearly not ***necessary*** for generalizations to take place. These results suggest that linguistic generalizations from signs are autonomous (Tzelgov, 1997), in the sense that they unfold even when they are not required by task demands. We now turn to consider the implication of this finding.

The Scope of Linguistic Generalizations in Sign Language

This research shows for the first time that signers extract the abstract structure of sign automatically, even in contrary to task demands, and they can do so even when the sign includes features that are unattested in their language. This finding is consistent with the hypothesis that signers represent their linguistic knowledge using abstract algebraic rules. Because the rule encodes the abstract constituent structure of entire classes (e.g., αα, where α stands for any syllable), it will extend a given generalization across the board, irrespective of whether its members are familiar or novel.

In line with this possibility, past research has shown that reduplication presents a challenge to various non-algebraic models. For example, Marcus (Marcus, 2001, 1998) systematically explored the generalization of the reduplication function in various connectionist networks (feed-forward and single recurrent networks). He found that these models successfully generalized the reduplication function as long as test items and training items shared their features (e.g., the labial feature in *baba* vs. *mama*). Critically, once test items comprised of features that were not presented in training, generalization failed. Berent and colleagues (2012) reported similar findings in their test of the maximum entropy model of phonology (Hayes & Wilson, 2008). Whether these failures reflect an inherent limitation of non-algebraic models, or whether they are specific to the settings of specific implementations remains a matter of controversy (e.g., Joanisse & McClelland, 2015; Smolensky et al., 2014; Westermann, 2016). So while across across-the-board generalizations are clearly suggestive of rule-based (i.e., algebraic) accounts of language, it is unclear whether these findings reject non-algebraic alternatives.

Our present investigation cannot settle the computational controversy concerning how the mind works. Nonetheless, these findings present an important empirical contribution to this debate. Indeed, the results from signers converge with past findings from spoken language (Berent et al., 2002; Marcus et al., 1999). In both modalities, people extend their linguistic knowledge across the board, even to items whose features are unattested in their language. The convergence demonstrates that the capacity to extend linguistic principles across the board is not restricted to spoken language. Unbounded productivity (Chomsky, 1972), then, is an inherent design feature of language faculty that is general with respect to input modality.

Notes

[1] We note that our definition of a rule differs from the technical linguistic notion. In the generative tradition (Chomsky & Halle, 1968) "rules" are defined as functions that map inputs to outputs, and they are contrasted with "constraints" (Prince & Smolensky, 1993/2004)—restrictions that apply to outputs only. In our definition, "algebraic rules" are operations over variables, and these can apply to *either* inputs or outputs. Accordingly, our notion of algebraic rules encompasses both linguistic notions.

[1] The hypothesis that mental computations include operations over variables is also known as the "symbolic hypothesis", and some have characterized the debate between proponents of the computational theory of mind and associations as a debate concerning the role of symbols. But as noted by Fodor and Pylyshyn (1988), this is a misnomer. Indeed, all sides assume the representation of symbols—the contention specifically concerns whether those symbols have internal structure that plays a causal role in mental computation. Following their lead, we thus frame the debate around the notion of rules.

[1] It is unlikely that the cost incurred by ABB forms is due to response competition per se, as the interference from ABB forms obtained even when their surface form was radically different from color words. Specifically, in these experiments, the critical novel forms (ABB, ABB, ABC) were presented in various morphological patterns, including ones that are highly affixed (e.g., *hitpapastem* vs. *hitpasasatem*, for PPS vs. PSS, respectively), and thus, quite different from the surface form of Hebrew color words (e.g., *adom, yarok, kaxol*, for *red, green* and *blue,* respectively). Not only did affixed ABB forms elicited robust interference but the magnitude of this effect was ***larger*** than the interference obtained for unaffixed forms (e.g., *papas, sapap*)—forms are more similar to color words. Given that the interference from ABB stems is independent of similarity to color words, this effect is most likely mediated by attention mechanisms.

[1] The capital letters denote the handshape in sign language.

[1] We note that this analogy is incomplete, inasmuch as the English illustration concerns a contrast of a single feature, whereas the handshape parameter in ASL is defined by several features.

[1] Despite their reduplicative structure, color signs in ASL are mono-morphemic. Whether signers indeed represent color terms as monomorphemic, or whether they are tempted to consider a bimorphemic parse (analogous to the possible bimorphemic parse of the English *sis**ter***) is unknown.

[1] Despite their reduplicative structure, neutral XX signs were not included in the analysis of reduplication for two reasons. First, the neutral signs were designed to as a control condition for the color-sign Stroop interference. Using the same materials to test the Stroop- interference and the reduplication effect would render those two manipulations non-independent. Second, unlike the αα signs, the XX neutral signs were not matched for feature composition to the αβ counterparts, so their comparison to αβ controls would confound the effect of reduplication with feature composition.

[1] To ensure that the effect of reduplication is not due to outliers in response time, we also conducted the ANOVA on the logarithm transformation of participants' mean response times. The main effect of reduplication was marginally significant ($F(1, 11)=4.79, p<.052$).

[1] To ensure that this effect is not due to extreme values, we also reanalyzed the response accuracy to nonnative signs using a mixed-effects logistic regression model, with reduplication as fixed effect (sum-coded) and participants and items as random effects (Color was removed from the analysis, its inclusion did not allow the model to converge). The effect of reduplication was marginally significant ($\beta=-0.4476$, $SE=0.2501$, $Z=-1.79$, $p<.074$).

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References

Albright, A., & Hayes, B. (2003). Rules vs. analogy in English past tenses: a computational/experimental study. *Cognition, 90*, 119-161.

Baus, C., Gutiérrez-Sigut, E., Quer, J., & Carreiras, M. (2008). Lexical access in Catalan Signed Language (LSC) production. *Cognition, 108*, 856-865.

Baus, C., Gutiérrez, E., & Carreiras, M. (2014). The role of syllables in sign language production. *Frontiers In Psychology, 5*.

Berent, I., & Shimron, J. (1997). The representation of Hebrew words: Evidence from the Obligatory Contour Principle. *Cognition, 64*, 39-72.

Berent, I., Shimron, J., & Vaknin, V. (2001). Phonological constraints on reading: Evidence from the Obligatory Contour Principle. *Journal of Memory and Language, 44*, 644-665.

Berent, I. (2002). Identity avoidance in the Hebrew lexicon: implications for symbolic accounts of word formation. *Brain and Language, 81*, 326-341.

Berent, I., Marcus, G. F., Shimron, J., & Gafos, A. I. (2002). The scope of linguistic generalizations: evidence from Hebrew word formation. *Cognition, 83*, 113-139.

Berent, I., & Shimron, J. (2003). Co-occurrence restrictions on identical consonants in the Hebrew lexicon : Are they due to similarity? *Journal of Linguistics, 39*, 31-55.

Berent, I., Vaknin, V., & Shimron, J. (2004). Does a theory of language need a grammar? Evidence from Hebrew root structure. *Brain and Language, 90*, 170-182.

Berent, I., & Marom, M. (2005). The skeletal structure of printed words: Evidence from the Stroop task. *Journal of Experimental Psychology: Human Perception & Performance, 31*, 328-338.

Berent, I., Pinker, S., Tzelgov, J., Bibi, U., & Goldfarb, L. (2005). Computation of semantic number from morphological information. *Journal of Memory and Language, 53*, 342-358.

Berent, I., Bibi, U., & Tzelgov, J. (2006). The autonomous computation of linguistic structure in reading: Evidence from the Stroop task. *The Mental Lexicon, 1*, 201-230.

Berent, I., Vaknin, V., & Marcus, G. (2007). Roots, stems, and the universality of lexical representations: Evidence from Hebrew. *Cognition, 104*, 254-286.

Berent, I., Wilson, C., Marcus, G., & Bemis, D. (2012). On the role of variables in phonology: Remarks on Hayes and Wilson. *Linguistic Inquiry, 43*, 97–119.

Berent, I., Dupuis, A., & Brentari, D. (2013). Amodal aspects of linguistic design. *Plos One, 8*.

Berent, I., Dupuis, A., & Brentari, D. (2014). Phonological reduplication in sign language: Rules rule. *Frontiers in Language Sciences, 5*, 560.

Bosworth, R. G., & Emmorey, K. (2010). Effects of iconicity and semantic relatedness on lexical access in american sign language. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 36*, 1573-1581.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624-652.

Brentari, D. (1998). *A prosodic model of sign language phonology*. Cambridge, Mass.: MIT Press.

Brentari, D., Coppola, M., Mazzoni, L., & Goldin-Meadow, S. (2012). When does a system become phonological? Handshape production in gestures, signers and homesigners. *Natural Language & Linguistic Theory, 30*.

Bybee, J., & McClelland, J. L. (2005). Alternatives to the combinatorial paradigm of linguistic theory based on domain general principles of human cognition. *Linguistic Review, 22*, 381-410.

Bybee, J. L. (2008). Linguistic universals and language change. In J. Good (Ed.), *Linguistic universals and language change* (pp. 108-121). Oxford; New York: Oxford University Press.

Caselli, N. K., & Pyers, J. E. (2017). The Road to Language Learning Is Not Entirely Iconic: Iconicity, Neighborhood Density, and Frequency Facilitate Acquisition of Sign Language. *Psychological Science, 28*, 979-987.

Chomsky, N. (1957). *Syntactic structures*. Gravenhage: Mouton.

Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. New York: Harper & Row.

Chomsky, N. (1972). *Language and mind* (Enl. ed.). New York: Harcourt Brace Jovanovich.

Chomsky, N. (2005). Three factors in language design. *Linguistic Inquiry, 36*, 1-22.

Corina, D. P., & Knapp, H. (2006). Sign language processing and the mirror neuron system. *Cortex, 42*, 529-539.

Dalrymple-Alford, E. (1972). Associative facilitation and interference in the Stroop color-word task. *Perception & Psychophysics, 11*, 274-276.

Dupuis, A., & Berent, I. (2015). Lexical access to signs is automatic. *Language, Cognition and Neuroscience, 11*, 1-6.

Eimas, P., & Seidenberg, M. (1997). Do Infants Learn Grammar with Algebra or Statistics? *Science, 284,* 433.

Elman, J. (1993). Learning and development in neural networks: The importance of starting small. *Cognition, 48*, 71-99.

Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking Innateness: A connectionist perspective on development*. Cambridge: MIT press.

Elman, J. L. (2005). Connectionist models of cognitive development: where next? *Trends Cogn Sci, 9*, 111-117.

Emmorey, K., Lane, H. L., Bellugi, U., & Klima, E. S. (2000). *The signs of language revisited : an anthology to honor Ursula Bellugi and Edward Klima*. Mahwah, N.J.: Lawrence Erlbaum Associates.

Emmorey, K., Grabowski, T., McCullough, S., Damasio, H., Ponto, L., Hichwa, R., et al. (2004). Motor-iconicity of sign language does not alter the neural systems underlying tool and action naming. *Brain and Language, 89*, 27-37.

Entel, O., Tzelgov, J., Bereby-Meyer, Y., & Shahar, N. (2015). Exploring relations between task conflict and informational conflict in the Stroop task. *An International Journal of Perception, Attention, Memory, and Action, 79*, 913-927.

Flemming, E. (2001). Scalar and Categorical Phenomena in a Unified Model of Phonetics and Phonology. *Phonology, 18*, 7-44.

Fodor, J., & Pylyshyn, Z. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition, 28*, 3-71.

Fodor, J. A. (1975). *The language of thought*. Cambridge, Mass.: Harvard University Press.

Frisch, S., A., Pierrehumbert, J., B., & Broe, M. B. (2004). Similarity avoidance and the OCP. *Natural Language and Linguistic Theory, 22*, 197-228.

Gervain, J., Macagno, F., Cogoi, S., Peña, M., & Mehler, J. (2008). The neonate brain detects speech structure. *Proc Natl Acad Sci U S A, 105*, 14222-14227.

Gervain, J., Berent, I., & Werker, J. (2012). Binding at birth: Newborns detect identity relations and sequential position in speech. *Journal of Cognitive Neuroscience, 24*, 564-574.

Greenberg, J., H. (1950). The patterning of morphemes in Semitic. *Word, 6*, 162-181.

Haskell, T. R., MacDonald, M. C., & Seidenberg, M. S. (2003). Language learning and innateness: Some implications of compounds research. *Cognitive Psychology, 4*, 119-163.

Hayes, B., & Wilson, C. (2008). A maximum entropy model of phonotactics and phonotactic learning. *Linguistic Inquiry 39*, 379-440.

Hildebrandt, U., & Corina, D. (2002). Phonological Similarity in American Sign Language. *Language and Cognitive Processes, 17*, 593-612.

Jacoby, L., Lindsay, D., & Hessels, S. (2003). Item-specific control of automatic processes: Stroop process dissociations. *Psychonomic Bulletin & Review, 10*, 638-644.

Joanisse, M. F., & McClelland, J. L. (2015). Connectionist perspectives on language learning, representation and processing. *Wiley Interdisciplinary Reviews. Cognitive Science, 6*, 235-247.

Leben, W. (1973). *Suprasegmental phonology*. Cambridge, MA: MIT press.

Levin, Y., & Tzelgov, J. (2016). Contingency learning is not affected by conflict experience: Evidence from a task conflict-free, item-specific Stroop paradigm. *Acta psychologica, 164*, 39.

Liddell, S., & Johnson, R. (1986). American Sign Language compound formation processes, lexicalization and phonological remnants. *Natural Language and Linguistic Theory, 4*, 445–513.

Logan, G. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology, 12*, 523-553.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrate review. *Psychological Bulletin, 109*.

Marcus, G. (2001). *The algebraic mind: Integrating connectionism and cognitive science*. Cambridge: MIT press.

Marcus, G., F. (1998). Rethinking eliminative connectionism. *Cognitive Psychology, 37*, 243-282.

Marcus, G. F., Vijayan, S., Bandi Rao, S., & Vishton, P. M. (1999). Rule learning by seven-month-old infants. *Science, 283*, 77-80.

Marcus, G. F., Fernandes, K. J., & Johnson, S. P. (2007). Infant rule learning facilitated by speech. *Psychol Sci, 18*, 387-391.

Marom, M., & Berent, I. (2010). Phonological constraints on the assembly of skeletal structure in reading. *Journal of Psycholinguistic research, 39*, 67-88.

Marschark, M., & Shroyer, E. H. (1993). Hearing Status and Language Fluency as Predictors of Automatic Word and Sign Recognition. *American Annals of the Deaf, 138*, 370-375.

McCarthy, J. (1986). OCP effects: Gemination and antigemination. *Linguistic Inquiry, 17*, 207-263.

McCarthy, J., J. (1989). Linear order in phonological representation. *Linguistic Inquiry, 20*, 71-99.

McClelland, J. L., & Patterson, K. (2002). Rules or connections in past-tense inflections: what does the evidence rule out? *Trends Cogn Sci, 6*, 465-472.

McClelland, J. L. (2009). Phonology and perception: A cognitive scientist's perspective. In P. Boersma & S. Hamann (Eds.), *Phonology in perception* (pp. 293-314). Berlin: Mouton De Gruyter.

McClelland, J. L., Botvinick, M. M., Noelle, D. C., Plaut, D. C., Rogers, T. T., Seidenberg, M. S., et al. (2010). Letting structure emerge: Connectionist and dynamical systems approaches to cognition. *Trends in Cognitive Sciences, 14*, 348-356.

Ormel, E., Knoors, H., Hermans, D., & Verhoeven, L. (2009). The role of sign phonology and iconicity during sign processing: The case of deaf children. *Journal of Deaf Studies and Deaf Education, 14*, 436-448.

Oudeyer, P.-Y. (2001). The Origins Of Syllable Systems : an Operational Model. In J. Moore & K. Stenning (Eds.), *Proceedings of the 23rd Annual Conference of the Cognitive Science society, COGSCI'2001* (pp. 744-749): Laurence Erlbaum Associates.

Petitto, L. A., Holowka, S., Sergio, L. E., & Ostry, D. (2001). Language rhythms in baby hand movements. *Nature, 413*, 35-36.

Pierrehumbert, J. (1993). *Dissimilarity in Arabic verbal roots.* Paper presented at the Proceedings of NELS 23, GLSA, Departments of Linguistics, University of Massachusetts, Amherst, MA.

Pinker, S., & Prince, A. (1988). On language and connectionism: Analysis of a parallel distributed processing model of language acquisition. *Cognition, 28*, 73-193.

Pinker, S. (1997a). Words and rules in the human brain. *Nature, 387,* 547-548.

Pinker, S. (1997b). *How the mind works*. New York: Norton.

Prince, A., & Smolensky, P. (1993/2004). *Optimality theory: Constraint interaction in generative grammar*. Malden, MA: Blackwell Publishing.

Proctor, R. W. (1978). Sources of color-word interference in the Stroop color-naming task. *Perception & Psychophysics, 23*, 413-419.

Rabagliati, H., Senghas, A., Johnson, S., & Marcus, G. F. (2012). Infant rule learning: Advantage language, or advantage speech? *Plos One, 7*.

Ramscar, M., & Dye, M. (2011). Learning language from the input: Why innate constraints can't explain noun compounding. *Cognitive Psychology, 62*, 1-40.

Rumelhart, D., E., & McClelland, J., L. (1986). On learning past tense of English verbs: Implicit rules or parallel distributed processing? In D. Rumelhart, E., J. McClelland, L & T. P. R. Group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 2, pp. 216-271). Cambridge MA: MIT Press.

Sandler, W., & Lillo-Martin, D. C. (2006). *Sign language and linguistic universals*. Cambridge: Cambridge University Press.

Sandler, W., Aronoff, M., Meir, I., & Padden, C. (2011). The gradual emergence of phonological form in a new language. *Natural Language and Linguistic Theory, 29*, 505-543.

Seidenberg, M., & McClelland, J. (1989). A distributed developmental model of word recognition and naming. *Psychological Review, 96*, 523-568.

Seidenberg, M. (1997). Language acquistion and use: Learning and applying probabilistic contraints. *Science, 275,* 1599-1603.

Seidenberg, M. S., & Jeffery, L. E. (1999). Do infants Learn Grammar with Algebra or Statistics. *Science, 284,* 433.

Smolensky, P., Goldrick, M., & Mathis, D. (2014). Optimization and Quantization in Gradient Symbol Systems: A Framework for Integrating the Continuous and the Discrete in Cognition. *Cognitive Science, 38*, 1102-1138.

Stokoe, W. C., Jr. (1960). Sign Language Structure: An Outline of the Visual Communication Systems of the American Deaf. *Journal of Deaf Studies and Deaf Education, 10*, 3-37.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643-662.

Supalla, T., & Newport, E. (1978). How many seats in a chair? The derivation of nouns and verbs in American Sign Language. In P. Siple (Ed.), *Understanding Language through Sign Language Research.* (pp. 91-132). New-York: Academic Press.

Thompson, R. L., Vinson, D. P., & Vigliocco, G. (2009). The link between form and meaning in American Sign Language: Lexical processing effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 550-557.

Thompson, R. L., Vinson, D. P., & Vigliocco, G. (2010). The link between form and meaning in British Sign Language: Effects of iconicity for phonological decisions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 1017-1027.

Thompson, R. L., Vinson, D. P., Woll, B., & Vigliocco, G. (2012). The road to language learning is iconic: Evidence from British sign language. *Psychological Science, 23*, 1443-1448.

Tzelgov, J., Henik, A., & Berger, J. (1992). Controlling Stroop effect by manipulating expectation for color related stimuli. *Memory & Cognition, 20*, 727-735.

Tzelgov, J. (1997). Specifying the relations between automaticity and consciousness: A theoretical note. *Consciousness And Cognition, 6*, 441-451.

Westermann, G. (2016). Experience-Dependent Brain Development as a Key to Understanding the Language System. *Topics In Cognitive Science*.

Wilbur, R. B. (1973). *The phonology of reduplication.* Unpublished Ph.D., University of Illinois at Urbana-Champaign, Ann Arbor.

Wilbur, R. B. (2009). Productive reduplication in a fundamentally monosyllabic language. *Language Sciences, 31*, 325-342.

Appendix A. The materials used in the reduplication manipulation.

	Reduplicated	Non-reduplicative
Native signs	AA	AD
	CC	CA
	DD	DC
Nonnative signs	11	12
		13
	22	21
		23
	33	31
		32

Note: All letters refer to the ASL handshape that corresponds with that letter. All numbers refer to handshapes that are nonnative in ASL, such that 1 = the Russian Sign Language ‘EE’, 2 = the Chilean Sign Language ‘P’ and 3 = the Portuguese Sign Language ‘H’.

Appendix B

Foreign handshapes used in the nonnative signs.

		
1. Russian Sign Language ‘EE’	2. Chilean Sign Language ‘P’	3. Portuguese Sign Language ‘H’

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[1] We note that our definition of a rule differs from the technical linguistic notion. In the generative tradition (Chomsky & Halle, 1968) "rules" are defined as functions that map inputs to outputs, and they are contrasted with "constraints" (Prince & Smolensky, 1993/2004)—restrictions that apply to outputs only. In our definition, "algebraic rules" are operations over variables, and these can apply to *either* inputs or outputs. Accordingly, our notion of algebraic rules encompasses both linguistic notions.

[2] The hypothesis that mental computations include operations over variables is also known as the "symbolic hypothesis", and some have characterized the debate between proponents of the computational theory of mind and associations as a debate concerning the role of symbols. But as noted by Fodor and Pylyshyn (1988), this is a misnomer. Indeed, all sides assume the representation of symbols—the contention specifically concerns whether those symbols have internal structure that plays a causal role in mental computation. Following their lead, we thus frame the debate around the notion of rules.

[3] It is unlikely that the cost incurred by ABB forms is due to response competition per se, as the interference from ABB forms obtained even when their surface form was radically different from color words. Specifically, in these experiments, the critical novel forms (ABB, ABB, ABC) were presented in various morphological patterns, including ones that are highly affixed (e.g., *hitpapastem* vs. *hitpasasatem*, for PPS vs. PSS, respectively), and thus, quite different from the surface form of Hebrew color words (e.g., *adom, yarok, kaxol*, for *red, green* and *blue,* respectively). Not only did affixed ABB forms elicited robust interference but the magnitude of this effect was ***larger*** than the interference obtained for unaffixed forms (e.g., *papas, sapap*)—forms are more similar to color words. Given that the interference from ABB stems is independent of similarity to color words, this effect is most likely mediated by attention mechanisms.

[4] The capital letters denote the handshape in sign language.

[5] We note that this analogy is incomplete, inasmuch as the English illustration concerns a contrast of a single feature, whereas the handshape parameter in ASL is defined by several features.

[6] Despite their reduplicative structure, color signs in ASL are mono-morphemic. Whether signers indeed represent color terms as monomorphemic, or whether they are tempted to consider a bimorphemic parse (analogous to the possible bimorphemic parse of the English *sis**ter***) is unknown.

[7] Despite their reduplicative structure, neutral XX signs were not included in the analysis of reduplication for two reasons. First, the neutral signs were designed to as a control condition for the color-sign Stroop interference. Using the same materials to test the Stroop- interference and the reduplication effect would render those two manipulations non-independent. Second, unlike the αα signs, the XX neutral signs were not matched for feature composition to the αβ counterparts, so their comparison to αβ controls would confound the effect of reduplication with feature composition.

[8] To ensure that the effect of reduplication is not due to outliers in response time, we also conducted the ANOVA on the logarithm transformation of participants' mean response times. The main effect of reduplication was marginally significant ($F(1, 11)=4.79$, $p<.052$).

[9] To ensure that this effect is not due to extreme values, we also reanalyzed the response accuracy to nonnative signs using a mixed-effects logistic regression

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model, with reduplication as fixed effect (sum-coded) and participants and items as random effects (Color was removed from the analysis, its inclusion did not allow the model to converge). The effect of reduplication was marginally significant ($\beta=-0.4476$, $SE=0.2501$, $Z=-1.79$, $p<.074$).