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Potentially recursive structures emerge quickly when a new language community forms

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ABSTRACT

Human languages can express an infinite number of thoughts despite having a finite set of words and rules. This is due, in part, to recursive structures, which allow us to embed one instance of a rule inside another. We investigated the origins of recursion by studying the development of Nicaraguan Sign Language (LSN), which emerged in the last 40 years and is not derived from any existing language. Before this, deaf individuals in Nicaragua lacked access to language models and each individual created their own gestural system, called homesign. We tested four groups: homesigners, who represent the point of origin, and the first three generations of LSN signers, who represent consecutive stages in the language's development. We used a task that was designed to elicit sentences with relative clauses, a device that allows for the recursive embedding of sentences inside of sentences (e.g., [the girl [who was drawing] removed the picture]). Signers in all three LSN cohorts consistently produced utterances that appeared to have embedded predicates (girl draw remove picture) which served the function of a relative clause (picking out the correct member of a set, based on previously mentioned information). Furthermore, in these utterances, the first verb was shorter than the second and shorter than the same verb in parallel unembedded structures. In contrast, homesigners produced similar utterances in embedded and unembedded contexts. They did not reintroduce previously mentioned information or produce reduced verb forms in the embedded context. These results demonstrate that syntactic embedding that is potentially recursive can emerge very early in a language. These embedded predicates, however, may not be widespread, or systematically marked, in homesign systems. This raises the possibility that the emergence of recursive linguistic structure is a consequence of interaction within a language community. These findings pave the way for future work which investigates the syntactic form of these embedded predicates and explores whether multiple levels of embedding are possible.

1. Introduction

Consider the sentence "John knows Mary knows Bill lied." The meaning of this sentence (its semantic form) involves a knowledge state (John's) that has another knowledge state embedded within it (Mary's) which has a third event embedded within it (Bill's lying). At the syntactic level, the sentence is expressed by using a clause embedded within a clause, embedded within another clause (Chomsky, 1980; Pinker & Jackendoff, 2005). Both of these representations are *recursive* because they are described by rules which call upon their own output, directly or indirectly. They have instances of a given type of representation embedded in another instance of the same type. Interpreting this sentence requires mapping the recursive syntax onto the recursive meaning.

Recursion has been argued to be universal and unique to human language, raising the possibility that this capacity might account for the gulf between human languages and other animal communication systems (Hauser, Chomsky, & Fitch, 2002). However, at least one language, Pirahã, has been said to lack syntactic recursion (Everett, 2005; Futrell, Stearns, Everett, Piantadosi, & Gibson, 2016 but see Nevins, Pesetsky, & Rodrigues, 2009; Sauerland, 2015). Instead of embedding clauses within clauses or noun phrases within noun phrases, it has been proposed that Pirahã expresses embedded meanings ("Mary's sister's house") through parataxis ("Mary has a sister. This sister has a house," see Everett, 2005).

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Everett's analysis of Pirahã is controversial (Nevins et al., 2009; Sauerland, 2015). For example, Sauerland (2015) argues that Pirahã has a complementizer that marks embedded clauses, providing evidence for sentential recursion. We will return to this issue in the General Discussion.

Critically, however, this debate has raised questions about the origins of syntactic rules in the evolution of language, which cannot be resolved by looking at Pirahã alone. A capacity for recursive rules could be a robust property of the human mind and human languages, but they could be absent in Pirahã due to a fluke of history. After all, languages vary in which syntactic rules are recursive (Roeper, 2011), so perhaps Pirahã represents the boundary case in which all potentially recursive rules are absent, or perhaps recursive structures existed previously in the language and disappeared.

Alternatively, recursive rules could be a cultural achievement that arose slowly over historical time as each generation of users reanalyzed their input, resulting, gradually, in more complex rules and structures. The challenge for such an account would be to explain why so many languages arrived at similar solutions. This challenge could be met by identifying functional constraints intrinsic to communication that bias systems toward similar solutions. After all, there are other cases where convergent cultural evolution results in similar cognitive breakthroughs (see e.g., Chinese and Greek mathematics, Boyer & Merzbach, 2011) and these mental inventions can spread extensively through contact, with more isolated groups continuing to operate without them. In fact, several historical linguists have argued that sentence-level recursion is a relatively recent historical invention (e.g., Deutscher, 2000; Sampson, 2009; Steels, 2016). On this hypothesis, it would not be surprising if some languages, like Pirahã, lacked recursion—just as it is unsurprising that for thousands of years most human cultural groups lacked an algorithm for exact multiplication.

These two hypotheses—recursion as a property of the human mind vs. recursion as an historical achievement—make radically different predictions about how quickly recursion should emerge in a language that is created de novo. If the capacity to construct recursive rules is one facet of the human language endowment, one might expect recursive rules to appear early, as soon as the relevant grammatical structures are present and available to embed in one another (e.g., single clauses or noun phrases). Note that these data would be ambiguous as to whether an early emergence of recursion in LSN would be due to a linguistic capacity which all humans share or whether it is present in LSN because we have a broader conceptual capacity for recursion which all humans share. Alternatively, if recursion is an historical creation, like multiplication, that represents an accumulation of human knowledge, one would expect it to appear only after many generations of non-recursive language use. In this paper, we leverage the recent development of Nicaraguan Sign Language (LSN[1]) from individual homesign systems to track the emergence of linguistic structures that are potentially recursive.

In the remainder of this introduction, we do three things. First, we review the history of LSN (Section 1.1). Next, we evaluate the prior evidence for recursive structures in emerging languages in light of a three-step framework for studying syntactic structure in a new language (Section 1.2). Finally, we discuss our approach, why we targeted relative clauses, and how relative clauses are expressed in spoken and signed languages (Section 1.3).

1.1. The history of LSN

Before the 1970s, deaf people in Nicaragua had few opportunities to interact, and consequently there was no common sign language. Individuals in these circumstances often come up with gestural systems, called homesign, for communicating with family members. Homesign forms are generally not used consistently in a wider communicative context.

The social landscape in Nicaragua changed drastically with the establishment of a school for special education in the mid-1970s, followed by a vocational program for adolescents in the 1980s. Initially, teachers conducted lessons in spoken Spanish, which the students were unable to learn. However, the children communicated with each other using the homesign gestures that they had created within their families. These gestures developed into a new sign language (Brentari & Coppola, 2012; Coppola & Senghas, 2010; Kegl & Iwata, 1989; Kegl, Senghas, & Coppola, 1999; Polich, 2005; Senghas, Senghas, & Pyers, 2005). Each successive cohort of children introduces new grammatical forms into the language. Despite social contact between generations, once signers become adults, they do not adopt the grammatical changes introduced by younger signers (Senghas & Coppola, 2001; Senghas, Kita, & Özyürek, 2004). Consequently, older signers today represent earlier stages of the language relative to younger signers.

Similar processes have occurred around the world, both when deaf people are brought together in newly created schools (Woll, Sutton-Spence, & Elton, 2001) or in communities with a high incidence of hereditary deafness. Other recent cases of naturally emerging sign languages include Al-Sayyid Bedouin Sign Language (ABSL), Central Taurus Sign Language (CTSL), Chatino Sign Language, and others (Sandler, Meir, Padden, & Aronoff, 2005; Ergin, 2017; Hou, 2018). In the present study we explore whether there are recursive structures in the first three cohorts of LSN signers and in homesigners living in Nicaragua. But first, we review the prior literature on recursive structures in emerging languages.

1.2. Prior work on recursion in homesign and emerging sign languages

Demonstrating that a particular device, like recursion, is present in a language involves three steps which build upon one another.

Step 1: Identify strings with the relevant meaning that contain the words and word order that we would expect for a recursive utterance. For example, identifying sentences that contain possible relative clauses, where there are two clauses, one embedded within another. This is best done by eliciting utterances so that the meaning can be evaluated independently of the string itself.

Step 2: Demonstrate systematic differences between these strings and parallel strings with non-embedded meanings, ideally through systematic elicitation. For example, comparing sentences containing possible relative clauses and sentences containing conjoined clauses, where the clauses are not embedded, one within another.

Step 3: Rule out alternative analyses via elicitation of a variety of embedded utterances and a variety of controls. Demonstrate recursion (vs. a single level of embedding) by eliciting utterances with multiple embeddings to demonstrate these are truly recursive structures.

These steps constitute an outline for a research program that would, necessarily, occur in stages over the course of decades, yielding important insights at each step in the process. To date four studies have explored the use of potentially recursive utterances in emerging languages. All four of these studies have addressed the first step, finding evidence for what appear to be possible recursive messages (strings with recursive meaning) in corpora of spontaneous and elicited sign. Critically, none of these studies has taken an experimental approach, eliciting parallel embedded and non-embedded structures, and thus Step 2 remains to be done.

The first study exploring recursion in an emerging language is an investigation of six child homesigners conducted by Goldin-Meadow (1982). The author identified 66 sentences that seemed to express recursive messages in her extensive corpus of homesign (e.g., move palm eat, to mean "you move to my palm the grape which one eats"). All but

[1] Following Gagne (2017), we use LSN as the initialism for Nicaraguan Sign Language. This reflects our best information about the community's current preference for representing the name of the language: Lengua de Señas Nicaragüense. Previous initialisms include NSL and ISN.

one of these utterances were produced by one child ("David"). Many of these utterances appear to have an alternative analysis in which they are conjoined clauses (e.g., You move the grape to my palm and I will eat it). While conjoined clauses are analyzed as recursive in many grammatical frameworks (S → S + S), some researchers have argued that sequences of this kind can be analyzed as non-recursive adjacent sentences (e.g., Everett, 2005; Futrell et al., 2016).

The second study is an observational study by Kastner and colleagues of an emerging language, Kafr Qasem Sign Language (KQSL) which is approximately 100 years old (Kastner, Meir, Sandler, & Dachkovsky, 2014). KQSL has been in contact with Israeli Sign Language (ISL) for over forty years but does not appear to have extensive lexical overlap. The authors found 10 candidate examples of embedded predicates (WOMAN MAN SIT EYE-LOOK-AT to mean the woman is looking at the man who is sitting) in users from the second and third generation of KQSL signers.

A third study looked at the development of relative clause marking in three age groups of users of ISL using an elicitation task (Dachkovsky, 2017). ISL is the established signed language of Israel. It is approximately 90 years old and has roots in signed languages of Europe and the Middle East. Dachkovsky found that older signers produced a nonmanual marker (a forward head movement) when producing a relative clause, which aligned with the noun only (English translation: "The girl who is riding a rocking horse is eating an ice cream"). Younger signers, in contrast, used two nonmanual markers (the forward head movement and an eye squint) when producing relative clauses, which aligned with the whole relative clause (English translation: "The girl riding a rocking horse is eating an ice cream"). This shift suggests that for the younger signers the noun and the following verb form a constituent, suggesting that the verb is embedded in the noun phrase. This data is particularly relevant for the present paper because it suggests that emerging languages have potentially recursive syntax in addition to recursive messages. Specifically, by holding the nonmanual marker over the first predicate (but not the second) the younger signers appear to be marking the phrase structure of the utterance, indicating that the first clause is embedded within the noun phrase.

The final study, by Kegl and Stickney (2002) elicited relative clauses from six LSN signers using a production task based on Hamburger and Crain (1982). An experimenter acted out a story with two identical toys while a second experimenter and the participant watched. At the end, the second experimenter covered her eyes and the first experimenter pointed to one of the toys. The participant was asked to instruct the second experimenter to pick up the toy that the first experimenter had pointed to (e.g., Pick up the pizza that the man ate). They report that four out of the six signers produced forms that they interpreted as relative clauses. Their analysis focused on the LSN signer who produced the most consistent responses: a man who had entered the community in 1989. This signer produced internally headed relative clauses, relative clauses with full nouns in the embedded clause rather than in the matrix clause (e.g., MAN PIZZA ATE PICK-UP, relative clause underlined). This signer also produced a nonmanual marker (lower lip down and to the right and a forward head tilt) at the end of the suspected relative clause (after ATE above). The authors interpreted this nonmanual as an index that marks the position of the head noun in the matrix clause (the object in the SOV construction). These observations strongly suggest that relative clauses are present in LSN. There are, however, reasons to be cautious in interpreting these findings: the primary analysis is based on a single signer and the study has not been subject to peer review. Thus these observations point to the urgency of systematic, peer-reviewed work on relativization in emerging languages.

Taken together, these studies suggest that recursion can arise rapidly in emerging languages, perhaps in the first generation (Goldin-Meadow, 1982) or perhaps in the second or third (Dachkovsky, 2017; Kastner et al., 2014; Kegl & Stickney, 2002). We build on the prior work in the following ways.

First, none of these studies have used the same task, materials and analysis with homesigners, the first generation of language users, and users from subsequent generations. Thus we have limited information about how potentially recursive structures change as a language develops (but see Dachkovsky, 2017 above for change at a later stage).

Second, the first two studies used spontaneous production and thus the researchers had to infer the meaning of the sentences based on the sentence content and context. This raises the possibility that the signer had a different meaning in mind, possibly one with no conceptual or syntactic embedding. Embedding constrains semantic composition such that the meaning of an utterance systematically depends on which clause is embedded in the other ("The numbers that are prime are odd" is true while "The numbers that are odd are prime" is not). In many cases, however, the context will not clearly indicate the intended meaning. For example, in many of the situations where one can say "The girl that is riding a horse eats ice cream" it will also be true that "The girl who eats ice cream is riding a horse" and that "The girl eats ice cream and rides a horse."

Three, none of these studies explored whether systematic varying of the message context to highlight embedded vs. non-embedded propositions would result in systematically different utterances (embedded vs. non-embedded syntax). Thus, while the prior work has made considerable progress on Step 1 (as discussed above), Steps 2 and 3 remain to be done. In the present paper we focus on Step 2 by conducting systematic comparisons between sentences elicited in contexts where we would expect embedding and contexts where we would not expect embedding. In the General Discussion we begin considering Step 3, recognizing that it is a reiterative process that will require multiple experiments testing the alternative hypotheses as they arise.

Even if the findings of the previous studies are taken as strong evidence for recursion in these emerging languages, there is still good reason to look closely at a different language community. Emerging languages differ along many dimensions, all of which may have an effect on when recursive structures emerge: the size of the community, the role of child vs. adult learners in the community, the degree of contact with other signed and spoken languages, and the presence of hearing L2 learners of the language (Senghas, 2005). Determining whether recursion arises across a range of emerging languages will be critical to understanding its origins.

1.3. Our approach

The present study uses the recent development of LSN from individual homesign systems to track the emergence of embedded and potentially recursive linguistic structures. We accomplish this by constructing stimuli to elicit both embedded structures (relative clauses) and carefully matched unembedded utterances (conjoined clauses) and then comparing responses in these two conditions to determine whether the two types of messages are conveyed in distinct ways and how that changes as the language develops. This allows us to objectively define the set of candidate embedded utterances without relying on either intuitions about their meaning or potentially circular criteria (e.g., dividing utterances based on differences in form and using the difference in form to argue for a difference in meaning).

We focused on eliciting sentences with relative clauses. Relative clauses are clauses embedded within noun phrases, which may, in turn, be embedded within main clauses, as in the present study (Keenan, 1985; Pfau & Steinbach, 2005). The rules involved in their construction are, as a set, recursive, because the output of 1b can be an input of 1a.

1a. Sentence → Noun Phrase + Verb Phrase

1b. Noun Phrase → (Determiner) + Noun + Sentence

Relative clauses function to pick out a referent from a set of alternatives (e.g., "the girl who is drawing" from a set of girls). In this paper, we focus on relative clauses that modify subject nouns. We do this for two reasons. First, these constructions present a strong test of embedding as they are a case of nested recursion, in which one constituent is embedded in the middle of another constituent. Embedded constituents

that appear at the beginning or at the end of sentences, so called tail recursion, can be difficult to distinguish from iteration, when items are concatenated without adding hierarchical structure (e.g., Parker, 2006). Second, relative clauses are recursive in many languages (Roeper, 2011), and thus seem like a good place to begin our search, in contrast with structures like possessive nouns, or compound nouns, that are more cross-linguistically variable (Roeper, 2011; Snyder, 2001). Finally, relative clauses are common in both spoken and written language and can be elicited in children as young as two (McKee, McDaniel, & Snedeker, 1998) suggesting that the construction, and the task used to elicit it, might be suitable for adults with little or minimal literacy.

While relative clauses are recursive in a wide range of languages, their form varies considerably, both in signed and spoken languages (e.g., Keenan, 1985; Pfau & Steinbach, 2005). In English, relative clauses are preceded by a head noun phrase followed by a relativizer, such as a relative pronoun, like *the girl who was drawing removed the picture*. The relativizer can be omitted as in *the girl drawing removed the picture*. Not all languages employ relative pronouns like *who*, or complementizers like *that*. Many do not have relativizers and the relative clause is not overtly marked (Comrie & Kuteva, 2013).

Sign languages show similar typological variation. In American Sign Language (ASL), some relative clauses are head-internal, where the head noun phrase occurs within the relative clause, and marked with obligatory nonmanual markers and an optional manual sign for the relative pronoun THAT (Emmorey, 2002; Liddell, 1980; Padden, 1988). Nonmanual markers are facial and body movements which are often coarticulated with manual signs and carry grammatical information across different levels of linguistic representation, from phonology to discourse (Sandler & Lillo-Martin, 2006). Relative clauses in ASL can be nonmanually marked with an eyebrow raise, backwards head tilt, and a raised upper lip (Liddell, 1978; Liddell, 1980). In German Sign Language (DGS), relative clauses are head-external and contain an obligatorily relative pronoun marked by an eyebrow raise (Pfau & Steinbach, 2005). British Sign Language (BSL) does not have manual signs for relative pronouns, relying on nonmanual and prosodic cues to mark relative clauses (Sutton-Spence & Woll, 1999). In other words, in many languages, signed and spoken, a string of words with an embedded relative clause does not exhibit any overt morphosyntactic marking of that embedding.

From prior research, we had two expectations about the form that relative clauses would take in LSN. First, since subjects precede verbs in LSN, for relative clauses modifying the subject of a sentence, we expected strings in which the main noun is followed by the embedded verb and then by the main verb. Second, we expected verbs within relative clauses to be shorter in duration than verbs in non-embedded contexts, providing visible evidence of the embedding (Senghas, 1995). As in other sign languages (see Goldin-Meadow, 1982), in LSN, anaphoric predicates (which refer to a previously mentioned entity) are smaller and quicker. We assumed that the verbs in candidate relative clauses would follow this generalization.

Note that relative clauses are not the only way to pick out one character from a set. Participants could use parataxis. Parataxis (derived from a Greek word to mean "placing side by side") is a strategy where clauses are placed one after another, either without conjunctions or with coordinate (but not subordinate) conjunctions to describe conceptually embedded messages. For example, the event above might be described by signing GIRL DRAW GIRL REMOVE PICTURE. This is the strategy, which is argued to be used in Pirahã, we might expect to see if the language lacks recursion. In the present study, we investigate the development of embedding and potential recursion in homesign and LSN. We use tightly controlled elicitation contexts to reduce the need for interpretation and compare utterances elicited in recursive elicitation contexts and minimally different non-embedded contexts.

2. Methods overview

We designed stimuli to elicit relative clauses and non-embedded, control utterances. We use these stimuli for three experiments, two testing the first three age cohorts of LSN signers and one testing Nicaraguan adult homesigners.

Across three experiments, we take the first two steps outlined in section 1.2 designed to test whether there is embedding and potential recursion present in the language. In Experiment 1, we set out to identify strings with the relevant meaning and the words and word order we might expect for an embedded structure (Step 1). Experiment 2 builds on Experiment 1, eliciting utterances using tightly controlled contexts to investigate whether there are systematic differences between the embedded and potentially recursive strings and parallel non-embedded strings (Steps 1 and 2). Experiment 3 investigates whether there is evidence for embedded utterances in homesigners, who represent the origin point for LSN.

2.1.1. Procedure

All three experiments employed an elicited description task. Participants viewed a series of brief videoclips. After viewing each video clip, participants were asked to describe what happened. Participants were able to watch the clips more than once, if they desired. Descriptions were videotaped and coded offline.

All participants gave consent to participate and be videotaped as part of this study, and all were paid for their participation. The research protocol was approved by the Barnard College Institutional Review Board for the Protection of Human Subjects in Research and by the University of Connecticut Institutional Review Board for the Protection of Human Subjects in Research.

2.1.2. Coding

The data were coded by the first author who has 9 years of experience working with LSN, using the ELAN video and audio annotation program (http://tla.mpi.nl/tools/tla-tools/elan/) developed by the Max Planck Institute for Psycholinguistics (Lausberg & Sloetjes, 2009; Wittenburg, Brugman, Russel, Klassmann, & Sloetjes, 2006).

Signs were coded as starting when there was a change in the movement from the start position (if hands were at rest) or the previous sign (i.e., the transitional movement which starts at the end hold of the previous sign and ends at the beginning hold of the next sign), a changing of the handshape, and/or a change in facial expression or eye gaze. Signs were coded as ending when the signer stopped moving the hands, there was a contact break in the handshape, transition movement, and/or there was a change in facial expression or eye gaze. These cues were selected based on prior work demonstrating that they are reliably used by signers and non-signers to determine sign and clausal boundaries (e.g., Green, 1984; Fenlon, Denmark, Campbell, & Woll, 2007). Nominals were coded as present if there was (a) a lexical sign (e.g., **GIRL** DRAW REMOVE PICTURE), (b) an indexical nominal point, (c) a point to a location in space previously associated with a referent (e.g., **IX** DRAW REMOVE PICTURE), or (d) some combination (e.g., IX GIRL DRAW REMOVE PICTURE) before the verb (Comrie & Kuteva, 2013; Engberg-Pedersen, 1993; McBurney, 2002; Meier, 1990; Padden, 1988). Manual deictic gestures that referred to a person, including points with a hand or finger, toward some location in the signing space or directed toward a part of the signer's body (usually the chest), were coded as points.

The second author, who has 28 years of experience with LSN, performed reliability coding of the duration of the verb lengths used to determine the ratio of the length of the first verb to that of the second in the utterances produced by 30% of the signers across the three conditions. The correlation between the primary coder and the secondary

coder for the verb length ratios was $r = 0.922$.

2.1.3. Data analysis

Using the R programming language, analyses were conducted using logistic and linear mixed effect regression models. For all models, *item* and *subject* were entered as random effects. For logistic models, the presence of each variable of interest (e.g., *repetition* of the verb in the candidate relative clause) is entered as a 1, and its absence as a 0. All reported analyses coded *cohort* using two dummy variables, with the first cohort serving as the baseline (the intercept). Using the ANOVA function, we compared two models, one model with cohort or condition (depending on the analysis) as a predictor variable and one model without that variable. An example of our model specification, with cohort as a predictor variable, in the common glmer syntax is as follows: VerbRepetition ~ Cohort + (1|Trial) + (1|Subject), family = binomial ("logit"). If the ANOVA comparison was significant, indicating that the model with the variable of interest as a predictor was a better fit, we conducted follow-up comparisons to determine where the difference between groups lay.

The data associated with this article can be found at: https://osf.io/492b8/?view_only=8dc22f1d93a94c18b2ee05a9475503ea.

3. Experiment 1

Experiment 1 elicited relative clauses from three age cohorts of LSN signers.

3.1. Methods

3.1.1. Participants

Experiment 1 included 27 deaf Nicaraguan signers, all of whom were exposed to the emerging sign language by 6 years of age, and who use it as their primary daily language. Ten first-cohort signers (age M: 42 years) entered the community between 1974 and 1980 (age at entry M: 4 years). Ten second-cohort signers (age M: 31 years) entered the community between 1987 and 1990 (age at entry M: 4 years). Seven third-cohort signers (age M: 22 years) entered the community between 1994 and 1998 (age at entry M: 4 years).

3.1.2. Materials

Participants completed six trials in which they viewed brief videoclips and were asked to describe what happened in LSN. Each trial consisted of four short videoclips: the first three clips each depicted a different character engaged in an individuating action (e.g., drawing, writing, and knitting), to verify that signers distinguished the characters by their actions. The final videoclip depicted the three characters again performing their actions, and then depicted a new event involving only one of the characters (e.g., one girl removing a picture from the wall). An example of an embedded and potentially recursive structure, in which the first action (drawing) picks out which of the girls subsequently performed the second action (removing the picture), would be "The girl who was drawing removed the picture."

The order in which the target character appeared in the first three videos was counterbalanced. All three characters in each trial were the same apparent gender, with a similar appearance, and similar clothing. These choices ensured that the most relevant characteristic was the individuating action, maximizing the probability of successfully eliciting a relative clause. We will call these stimuli the *identifier + action* trials to differentiate them from the control conditions that appear in subsequent experiments.

3.1.3. Coding

A response was coded as having a candidate relative clause and included in the analysis if the signer first described the whole set of three characters and then produced an utterance which repeated the identifying action verb of the target character before describing the new action. Our motivation for this strict criterion of describing the set of characters is that it allows us to get at the question of whether the critical utterance serves the discourse function of a restrictive relative clause. To apply this criterion we had to determine that there was an utterance boundary between the description and the utterance with the candidate relative clause and that there was no utterance boundary between the identifying action and the action verb. To do this, we built on previous work on LSN which has documented the emergence of single utterances (rather than strings of signs) in the first cohort of signers. Utterance boundaries are systematically marked in LSN, as in many languages (e.g., Coulter, 1993; Kegl & McWhorter, 1997) by pauses and utterance final lengthening and thus these set of cues were used to determine the boundaries in our data set.

Descriptions that did not contain this information were coded as "other." Examples of "other" descriptions include cases in which the signer did not repeat the verb, instead describing the target individual last in the list of the three characters and then immediately describing the second action (e.g., GIRL PAINT, GIRL KNIT, GIRL DRAW REMOVE PICTURE); responses in which the signer identified only the target individual and his or her two actions (e.g., GIRL DRAW REMOVE PICTURE); and descriptions with a noun phrase picking out the referent instead of a verb phrase (e.g., GIRL WITH BOOK REMOVE PICTURE).

3.1.4. Data analysis

Using the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2014), analyses were conducted using generalized logistic and linear mixed-effects models (Baayen, Davidson, & Bates, 2008).

3.2. Results

Signers from all three cohorts of LSN produced descriptions with the content and function of relative clauses. First, signers established the set, describing the characters and their initial actions. Specifically, in each cohort, a majority of responses included descriptions of the initial actions of all three characters (Cohort 1: 79%, Cohort 2: 77%, Cohort 3: 86%). Note that signers were not explicitly instructed to describe all three characters but many of them spontaneously did so. Next, participants in all of the cohorts typically followed these descriptions with an utterance about the critical character which contained two verbs, one picking out a member of the set (the candidate relative clause) and the other predicating something new of this individual (the candidate main verb). This resulted in a large number of trials which included seemingly embedded and potentially recursive utterances: utterances that included both the identifying action and the new action and that followed prior

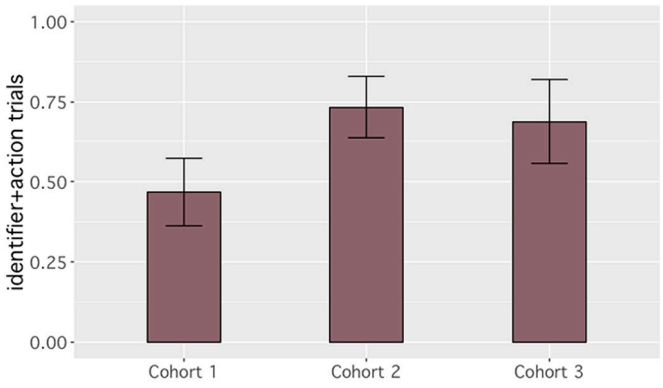

Fig. 1. Proportion of *identifier + action* trials in which signers produced utterances with the content and function of relative clauses in Experiment 1. Signers first established the set, then produced an utterance with two verbs, one picking out a member of the set, the candidate relative clause, and the other predicating something new of the member, the candidate main verb. Error bars represent +/− SEM.

descriptions establishing the set of characters (Cohort 1: 47%, Cohort 2: 73%, Cohort 3: 69%; see Fig. 1). An example of such a description appears in (2) below:

2. {GIRL DRAW}, {GIRL PAINT}, {GIRL KNIT}. {GIRL [DRAW] REMOVE PICTURE}.

The final string, with its two verbs, was the sentence containing the candidate relative clause. While such a string, in isolation, could express conjunction (the girl drew and removed a picture), this interpretation is unlikely in this context, since the action expressed by the first verb has already been completed and has already been mentioned, and thus is relevant only to the extent that it identifies which girl is under discussion.

We next looked at whether the surface form of the verb in the relative clause differed from a verb produced in a non-embedded context. We compared the two instances of the target verb that occurred in the descriptions containing candidate relative clauses: the initial use when the set of characters was described ({[GIRL **DRAW$_1$**], [GIRL PAINT], [GIRL KNIT]}), where the verb is not embedded, and the second use in the putative relative clause ({GIRL [**DRAW$_2$**] REMOVE PICTURE}), where the verb is embedded. We found that the second use of the verb (in the relative clause) was reliably shorter than the first use of the verb (in an unembedded context), specifically in the later cohorts of LSN users. Specifically a model with a variable for cohort was significantly better than a model without this variable [$\chi^2(2) = 7.44$, $p = .024$ for the comparison between the random effect model and the cohort model), indicating that cohort has an effect. Follow-up pairwise *t*-tests revealed a marginally significant difference between the first and second cohorts ($p = .087$), a significant difference between the first and third cohorts ($p = .007$), and no significant difference between the second and third cohorts ($p = .216$). Thus the youngest signers produce shorter forms of the embedded verb than the older signers, but the middle group is not significantly different from either of the other two.

3.3. Discussion

In Experiment 1, signers from all three cohorts of LSN produced descriptions with the content and function of relative clauses. First, they established the set, describing all three individuals and their initial actions; then, they produced an utterance with two verbs, one picking out a member of the set (the candidate relative clause) and the other predicating something new of this individual (the candidate main verb). The embedded verb in the relative clause was shorter than the main verb and this difference became more pronounced in the later cohorts.

4. Experiment 2

Experiment 2 sought to replicate our findings from Experiment 1 as well as elicit control utterances from three age cohorts of LSN signers.

4.1. Methods

4.1.1. Participants

Experiment 2 included 26 deaf LSN signers. Twenty-three of the 26 signers also participated in Experiment 1. Nine first-cohort signers (age M: 43 years) entered the community between 1974 and 1980 (age at entry M: 4 years). Nine second-cohort signers (age M: 32 years) entered the community between 1987 and 1990 (age at entry M: 4 years). Eight third-cohort signers (age M: 24 years) entered between 1994 and 1999 (age at entry M: 4 years). Twenty-three signers also participated in Experiment 1.

4.1.2. Materials

Fifteen base events, each with an *identifier + action* version, a *repeated action* version, and a *sequential action* version were created. As in Experiment 1, in the *identifier + action* version, the stimuli depicted three similar characters, each performing a distinct action (e.g., drawing, painting, or knitting; Fig. 2). One character (the girl drawing) then performs a new action (removing a picture from a wall).

The *sequential action* stimuli portrayed a single character performing two sequential actions (drawing then removing a picture). A non-recursive conjoined clause response would be "A girl drew and then removed a picture." The difference between the *identifier + action* and the *sequential action* versions was the presence of the two additional characters in the *identifier + action* version.

The *repeated action* stimuli portrayed one character engaged in the same action twice (drawing on paper and then drawing on an easel). This condition was designed to test whether merely repeating a verb could result in reduction, when the action description did not serve the function of a relative clause. A non-embedded repeated verb response would be "A girl drew on a piece of paper and then drew on an easel pad." We expected no verb reduction in either control condition. The difference between the *identifier + action* and the *repeated action* versions was the presence of the two additional characters in the *identifier + action* version, and the nature of the second action, which differed from the first action for the *identifier + action* trials.

Each of the actions, in all three versions, was 5 s in duration. This ensured that any reduction in the duration of the verb was not due to the length of the action itself. All videoclips were pretested on Amazon Mechanical Turk and found to successfully elicit the targeted structure in written English. For items in the *identifier + action* condition, the target structure was a sentence with a relative clause attached to the subject noun. For *sequential action* items, it was a sentence with a conjunction (either sentential conjunction or conjoined verb phrases), and for the *repeated actions*, it was a sentence with conjunction and two instances of the same verb.

Four lists were created and trial types were blocked. In half of the lists, the *identifier + action* trials appeared first. In the other half of the lists, the control trials appeared first. Participants completed a total of fifteen trials: six *identifier + action* trials, three *sequential action* trials, and six *repeated action* trials. The order of presentation of the four

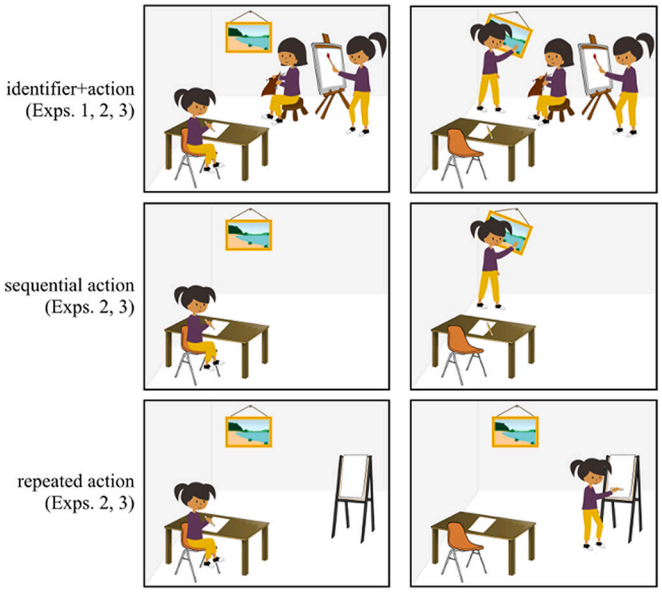

Fig. 2. Examples of stimuli. In the identifier+action condition, videoclips first depicted three similar-looking characters, each engaged in a different action. One of the three characters then carried out a second action. The target sentence contains a nominal with an embedded verb before the main verb (the girl who was drawing removed a picture). In the sequential action condition, a single character engaged in an action, followed by a second, different action (a girl drew and then removed a picture). In the repeated action condition, a single character engaged in an action, and then carried out the same action with a different object (a girl drew on a piece of paper, and then drew on an easel pad).

videoclips in the *identifier + action* trials was the same as in Experiment 1.

4.1.3. Data coding

As in Experiment 1, an utterance was coded as containing a candidate relative clause, and included in the analysis as such, if the signer described each of the three characters and then repeated the identifying action verb of the target character before describing the new action. Descriptions that did not contain this information were coded as "other."

For the control conditions: An utterance in the sequential action trials was included as a candidate case of conjunction if both actions were mentioned; 100% of the LSN utterances met this criterion. An utterance in the repeated action trials was included in the control analysis only if both actions were described by the same verb; 95% of the LSN utterances met this criterion.

4.1.4. Data analysis

Once again, analyses were conducted using logistic and linear mixed-effect models using the lme4 package in R.

4.2. Results

Experiment 2 replicated the findings of Experiment 1 and included control conditions that elicited non-embedded conjoined clauses and clauses with repeated actions (Fig. 2). Comparison of the utterances elicited in the identifier+action contexts with the sequential action and repeated action contexts confirmed our hypothesis that the identifier+action descriptions were embedded structures. The differences were clear (Fig. 3). On the identifier+action trials, LSN signers first described the set of three characters (Cohort 1: 93%, Cohort 2: 98%, Cohort 3: 100%), and then produced an utterance with two verbs: the first was a repetition of a previous verb, picking out an individual, and the second predicated something new of that individual (Cohort 1: 69%, Cohort 2: 81%; Cohort 3: 72%). In contrast, on sequential action trials, none of the responses, from any cohort, included a repetition of a previous verb (no cases like GIRL DRAW, GIRL DRAW REMOVE PAINTING). Thus, the responses in the identifier+action condition do not show the same discourse properties as otherwise similar conjoined utterances, supporting a recursion, rather than a parataxis analysis.

Because we hypothesized that the repetition strings were relative clauses, we examined how frequently these candidate relative clauses contained the expected embedded structure, with a nominal (the head noun) preceding the identifying verb (e.g., GIRL DRAW). Second- and third-cohort signers were significantly more likely to produce

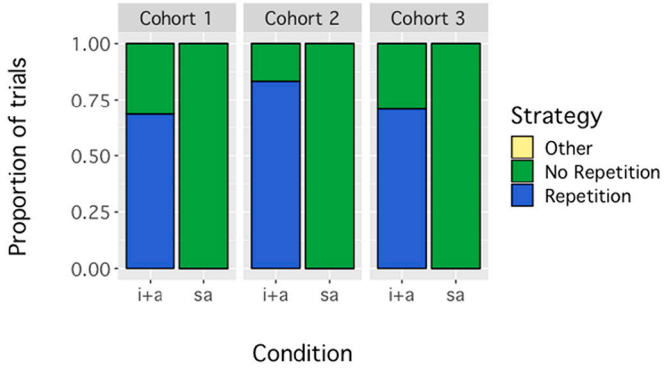

Fig. 3. Experiment 2 results. Evidence for embedding in LSN signers. Signers in all cohorts used verbal embedding (repeating the identifying verb) or the sequential verb strategy (no repetition of the identifying verb) in the identifier+action (i + a) condition, in which the doer of the second verb had to be selected from a set of possibilities. However, they did not use verbal embedding in the sequential action (sa) condition, when disambiguation was unnecessary (and infelicitous).

descriptions in the identifier+action trials with a nominal preceding the verb (Cohort 1: 27%, Cohort 2: 70%, Cohort 3: 82%, $\chi^2(2) = 11.01$, $p < .01$ for the comparison between the random effects model and the cohort model). Follow-up pairwise comparisons revealed that the difference between the first and second cohorts was significant ($p < .001$), as was the difference between the first and third cohorts ($p < .001$), with no significant difference between the second and third cohorts ($p = .280$). Further supporting our relative clause analysis, nominals seldom appeared after the identifying action had been described and before the new action (e.g., GIRL DRAW GIRL TAKE PICTURE; Cohort 1: 3%; Cohort 2: 2%; Cohort 3: 0%). Thus, these nominals appear to be the head nouns of the relative clauses, which are embedded within another clause.

Note there are other structures in natural languages in which nouns are modified by verbs (such as verbs used as adjectives, like "The running boy pushed the girl"). However, these alternative analyses would still be cases of embedded structures, though perhaps not of recursive structures. We discuss this further in the General Discussion.

To explore whether embedded verbs were reduced, we conducted two analyses. First, we compared the duration of the verb in the identifier+action descriptions (DRAW in {GIRL [**DRAW**] REMOVE PICTURE}) with the same verb in the sequential action descriptions (DRAW in {GIRL **DRAW**} {REMOVE PICTURE}). We conducted model comparisons to explore the effects of condition, cohort and their interaction. We found that these verbs were considerably shorter in the identifier+action descriptions (Fig. 4; $^2(1) = 29.00$, $p < .001$ for the comparison of the random effects model and the condition only model). Cohort was a predictor of verb length across conditions, with later cohorts producing shorter verbs [$\chi 2(2) = 8.88$, $p = .012$ for the comparison of the condition only model and the condition + cohort model]. However, there was no reliable interaction between condition and cohort [$\chi^2(2) = 3.77$, $p = .151$ for the comparison of the condition + cohort and condition * cohort models].

We looked at the identifier+action descriptions and compared the two instances of the target verb that occurred: the initial use when the

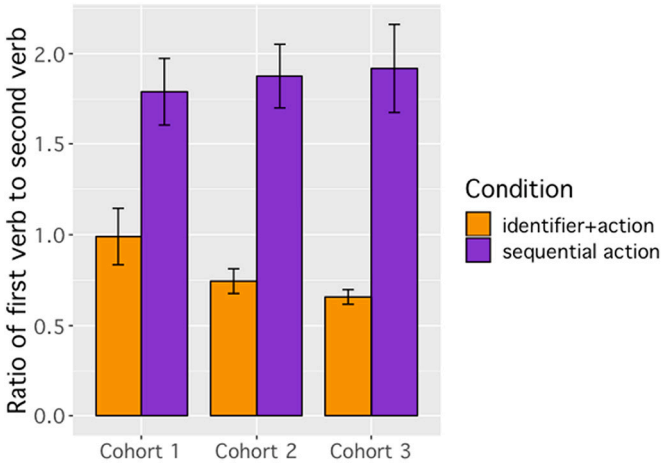

Fig. 4. Experiment 2 results. To detect formal evidence of embedding, we analyzed utterances containing two different verbs (e.g., DRAW and REMOVE). We then calculated the ratio of the duration of the first verb, DRAW, to the second verb, REMOVE. For all LSN groups, the first verb was the same duration or shorter than the second verb in the identifier+action condition (orange bars), but not in the sequential action condition (purple bars) [$\chi 2(1) = 19.97$, $p < .001$ for comparison of random effects model and condition model, $\chi 2(2) = 0.90$, $p = .639$ for comparison of condition model and condition + cohort model]. This systematic shortening that is restricted to the identifier+action condition suggests that the first verb, DRAW, is embedded, and functions as a relative clause that picks out the doer by referring to her earlier action ("the girl who drew"). Error bars represent +/− SEM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

set of characters was described ({[GIRL **DRAW$_1$**], [GIRL PAINT], [GIRL KNIT]}) and the second use in the putative relative clause ({GIRL [**DRAW$_2$**] REMOVE PICTURE}). We found an effect of cohort for the second use of the verb (in the relative clause) which was reliably shorter than the first use of the verb (in an unembedded context), but only for later cohorts. The comparison of the random effects model and the cohort model was significant [$\chi^2(2) = 10.44$, $p < .01$], indicating that cohort has an effect. As in Experiment 1, the duration of the verb in the relative clause was reduced compared to its first use in the younger signers. Follow-up pairwise *t*-tests showed a significant difference between the first and second cohorts ($p = .012$), between the first and third cohorts ($p = .002$), and no significant difference between the second and third cohorts ($p = .461$).

Second, to rule out the possibility that verb reduction was merely a side effect of repeating the same verb, we did a parallel analysis of the repeated action trials and found no evidence of verb reduction [$\chi^2(2) = 0.99$, $p = .611$ for the comparison between the random effects model and the cohort model]. Accordingly, verbs were reliably shorter in the identifier+action condition than in the repeated action condition [$\chi^2(1) = 11.86$, $p < .001$ for the comparison between random effects model and condition model, $\chi^2(2) = 7.11$, $p = .029$ for the comparison between condition model and condition + cohort model, $\chi^2(2) = 3.45$, $p = .178$ for the comparison between condition + cohort model and condition * cohort model], and there was no significant difference in the ratio of the duration of the first verb to the second verb in the repeated action descriptions across all cohorts [$\chi^2(2) = 0.17$, $p = .918$ for the comparison of the random effect model and the cohort model].

Note that this shortening of the verb cannot be attributed to effects of utterance-final lengthening. In both the critical condition and the sequential action condition the second verb is typically utterance final. Thus while it may be longer, it cannot account for any difference between them. Unsurprisingly, we found that the second verbs in these two conditions are quite similar in length: 955 msec in the identifier+action condition and 975 msec in the sequential action condition (see Supplementary Materials for additional analyses). The first verb, in both conditions is utterance medial but is considerably longer in the control condition, where it is presumably conjoined, than it is in the critical identifier-action condition where it appears to be embedded.

This verb shortening is also unlikely to be due to an effect of topicalization. The descriptions in the identifier+action condition are the cases where we are most likely to observe topicalization, because the identifier description (the candidate relative clause) is given information. If this identifying verb (DRAW) is carrying the topic marking, we might expect it to be longer or to be followed by a longer pause than a verb that did not mark the topic, since this is the pattern that has been observed in other signed languages. But we found the exact opposite pattern: the first verb (DRAW) was shorter in the identifier+action condition compared to the sequential+action condition.

Given the difference in verb length, we decided to further explore the possibility of prosodic differences between the conditions by looking at the temporal distance between the two verbs in each utterance. There is a close relationship between the syntax of an utterance and its prosody. When the phrase that is ending is longer or higher up in the tree, there is more likely to be a longer pause after it (see e.g., Snedeker & Casserly, 2010; Wagner, 2010). We hypothesize that the sequential action and repeated action utterances are instances of sentential conjunction, with each verb belonging to a different matrix clause. On this hypothesis there is a large syntactic break between the two verbs, which we expect would be marked with a prosodic break and a pause. In contrast, if the identifier+action descriptions contain a predicate embedded in a noun, then the first verb is part of a noun phrase that serves as the subject of the second verb. This is a smaller syntactic break, which would typically be marked with a shorter or more subtle prosodic break.

To test this hypothesis, we measured the temporal distance between the verb in the embedded clause and the verb in the matrix clause in the identifier+action descriptions, and between the verb in the first clause and the verb in the second clause in the sequential action and repeated action descriptions. On average, there was a shorter timing gap, in seconds, between the two verbs in the identifier+action descriptions (Cohort 1: 2.52, Cohort 2: 2.37, Cohort 3: 2.30) compared to the sequential action clauses (Cohort 1: 4.30, Cohort 2: 4.20, Cohort 3: 3.00) and the repeated action clauses (Cohort 1: 3.59, Cohort 2: 4.09, Cohort 3: 2.84). This systematic difference offers further evidence that the clauses in the identifier+action descriptions have a different structure than the sequential action and repeated action descriptions.

4.3. Discussion

Experiment 2 replicated the findings of Experiment 1 and included control conditions that elicited non-embedded conjoined clauses and clauses with repeated actions. We compared utterances elicited in the identifier+action contexts with the sequential action and repeated action contexts. The differences were clear. On the identifier+action trials, LSN signers first described the set of three characters and then produced an utterance with two verbs: the first was a repetition of a previous verb, picking out an individual, and the second predicated something new of that individual. In contrast, on sequential action trials, none of the responses, from any cohort, included a repetition of a previous verb (no cases like GIRL DRAW, GIRL DRAW REMOVE PAINTING). Thus, the responses in the identifier+action condition do not show the same discourse properties as otherwise similar conjoined utterances, suggesting that they are instances of embedding rather than parataxis.

Second, the critical utterances in the identifier+action contexts were produced in a systematically different way than the parallel utterances in the repeated action and sequential action conditions. Specifically, in the critical sentences the first verb was shortened (relative to the second verb and relative to the control conditions) and was quickly followed by the second verb. This is the pattern that we would expect if the first verb was embedded in the noun phrase and thus the juncture between the verbs was within the same clause rather than between two clauses. In contrast, in the control conditions the first verb was considerably longer and there was a substantial gap between the first and second verb. This is the pattern that we might expect to see if the two verbs were conjoined (either as VP or as clauses).

5. Experiment 3

Experiment 3 elicited relative clauses and control utterances from Nicaraguan adult homesigners.

5.1. Methods

5.1.1. Participants

Experiment 3 included 4 Nicaraguan adult homesigners (age M: 35 years). None of the four homesigners have regular contact with LSN or contact with a regular communication partner who knows LSN (Gagne, 2015). Following the same procedure as for LSN signers, the participants were shown the stimuli and asked to describe what happened. The descriptions were produced for the experimenter.

5.1.2. Materials

Experiment 3 used the same design as Experiment 2, except only one list was used. The identifier+action trials appeared first.

5.1.3. Data coding

We employed the same coding procedures used in Experiment 2.

5.1.4. Data analysis

As in Experiment 2, analyses were conducted using logistic and linear mixed-effect models.

5.2. Results

In Experiment 3, homesigners tested in the same three conditions as in Experiment 2, identifier+action, sequential action, and repeated action, yielded a very different pattern of results. In the identifier+action condition, all homesigners produced at least some utterances that described both the first and second action of the target character (GIRL DRAW REMOVE PICTURE, Fig. 5). These utterances, however, were very similar to their responses in the sequential action condition (Fig. 6). Specifically, on identifier+action trials, homesigners typically did not introduce the full set or repeat the identifying verb.

Homesigners did not introduce the set or repeat the identifying action in the identifier+action condition. A closer look at the descriptions, however, revealed that there were a few different strategies that homesigners used to disambiguate the target individual from the other characters in the set (Fig. 7).

Critical Character End, Both Actions: Descriptions contained mention of more than one character with the target individual appearing last immediately followed by a description of the second event. For example, LIFT-WEIGHT IX JUMP-ROPE EAT-PIZZA. Only a quarter of all descriptions contained mention of all three characters, and within that, only two employed this end strategy.

Only Critical Character, Both Actions: Descriptions contained mention of only the actor and action of the second event, avoiding the need for disambiguation. For example, GIRL DRAW REMOVE PICTURE.

Only Critical Action: Descriptions contained a noun phrase ("the man with the ball"), describing some attribute of the target character, followed by a verb phrase expressing the second action. For example, MAN BALL KICK TRASH-CAN.

To determine whether homesigners shortened the first verb in the identifier+action description we calculated the verb ratios as we had in the prior experiment. We found no evidence that the verb in the identifier+action descriptions was reduced relative to the verb in the sequential action descriptions for any of the homesigners [$\chi^2(1) = 0.66$, $p = .418$, Table 1].

Though the verb in the homesigners' identifier+action descriptions was not reduced relative to the verb in the sequential action descriptions, we examined the descriptions in all three conditions for possible prosodic differences. We measured the temporal distance 1) between the verb in the embedded clause and the verb in the matrix clause in the *critical character end, both actions* and *only critical character, both actions* descriptions that were produced in the identifier+action condition, and 2) between the verb in the first clause and the verb in the

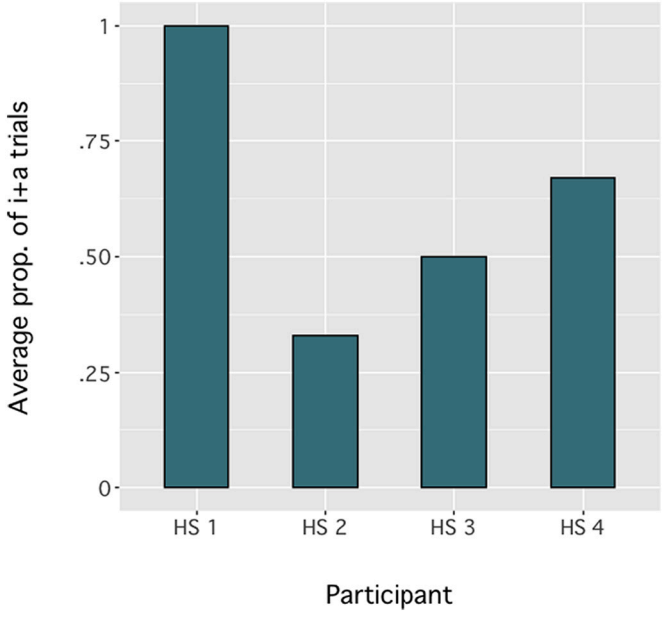

Fig. 5. Percentage of identifier+action trials in which homesigners described both the identifying and the new action of the target character.

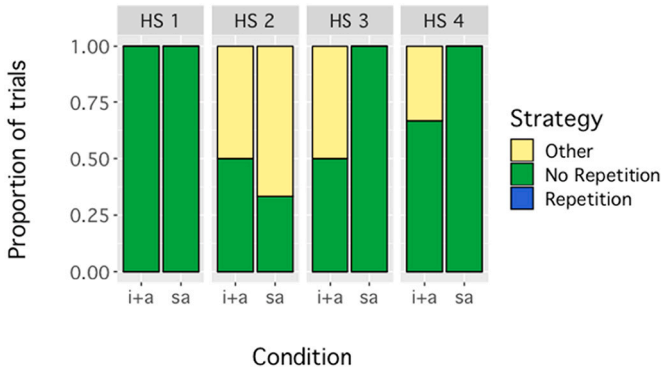

Fig. 6. Experiment 3 results. Homesigners, unlike the LSN signers, did not repeat the first verb (the identifying action) in the identifier+action (i + a) condition and thus their responses in this condition were more similar to the responses produced in the sequential action (sa) control condition. Trials coded as 'Other' did not include verbs for both actions.

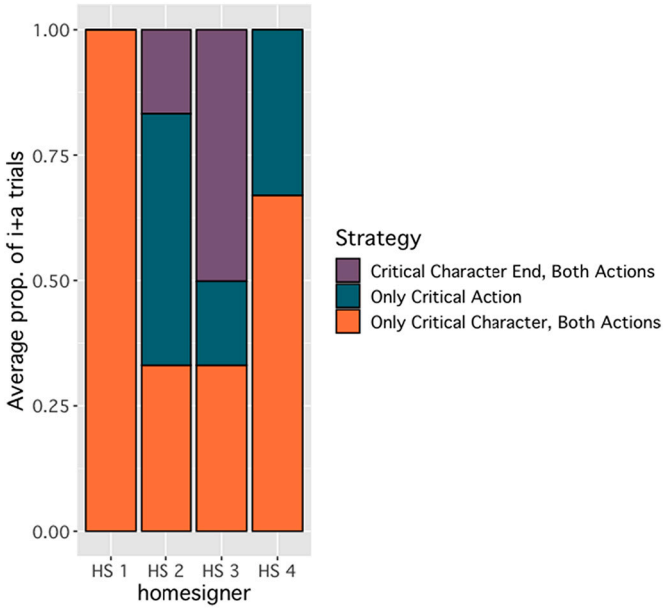

Fig. 7. The Critical Category End Both Actions category (purple bars) shows responses in which the participant described more than one character with the target character appearing last followed by a verb phrase expressing the second action. The Only Critical Character Both Action category (orange bars) shows responses in which the participant described only the actor and action of the second event (avoiding the need for disambiguation). Responses in the Only Critical Action category (teal bars) included producing a noun phrase ("the man with the ball") followed by a verb phrase expressing the second action. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Ratio of first verb to second verb across all conditions.

	identifier+action	sequential action	repeated action
Homesigner 1	0.91	0.77	1.00
Homesigner 2	1.35	1.00	1.39
Homesigner 3	1.18	1.52	0.91
Homesigner 4	1.31	1.44	1.39

second clause in the sequential action and repeated action descriptions. While there was variation across the homesigners, there was a marginally significant effect of condition with a shorter timing gap, in seconds, between the two verbs in the identifier+action descriptions compared to the sequential action and repeated action descriptions ($\chi^2(1) = 3.62, p = .057$, Table 2). Looking at the high-level pattern by condition, the averages by homesigner suggest that this difference in timing gap across conditions appears in three of the four homesigners.

Thus, while many of the descriptions in the identifier+action condition appeared similar to the descriptions in the sequential action, and there was no verb reduction, there does appear to be a difference in timing between the identifier+action descriptions and the control conditions for at least some of the homesigners. Note that as we only used one list with homesigners, it is possible that these timing differences could be attributed to differences in the items. Thus, we must interpret this pattern with caution.

That being said, there are two possible contributors to a bigger timing gap between the verbs. First, there could be additional words between the verbs in the control conditions. For example, the head noun might be repeated more often in the sequential action condition (GIRL DRAW GIRL REMOVE PICTURE). This difference would be consistent with our hypothesis that the control utterances are conjoined sentences while the utterances in identifier+action condition contain embedded predicates. Responses of this kind, however, were quite rare (one across all 4 signers) and thus they cannot account for the observed differences.

Second, there could be a pause, or a longer pause, after the verb in the sequential action and repeated action conditions. As noted above, this pattern would be expected on the analysis in which the first verb in the identifier+action condition is embedded within the subject noun phrase. One might wonder why this larger prosodic break did not affect the length of the first verb. One reasonable hypothesis is that utterances of both kinds had a prosodic break of some kind (resulting in phrase final lengthening) but the prosodic break was simply larger in the control conditions. In general, when production is slow, as it often is in homesign, there are more frequent prosodic breaks. Across a range of speeds, however, the relative magnitude of prosodic breaks appears to reflect syntactic structure (Snedeker & Casserly, 2010).

5.3. Discussion

In Experiment 3, we found a different pattern in homesigners compared to LSN signers. In the identifier+action contexts, LSN signers first described the set of three characters and then produced an utterance with two verbs, where the first verb was a repetition of a previous verb, picking out an individual, and the second predicated something new of that individual. In contrast, homesigners often produced utterances that described only the first and second actions of the target character. Thus most of the descriptions in the identifier+action contexts were very similar to the descriptions in the sequential action condition. In addition, when both verbs were produced, the identifying verb was not reduced in length.

In three of the homesigners, however, there appeared to be prosodic differences between the descriptions produced in the identifier+action condition and the descriptions produced in the control conditions. Specifically, there was a longer timing gap between the verbs in the control conditions. While this data pattern is open to many interpretations, we tentatively suggest that homesigners' are producing descriptions that convey embedded meanings, that this results in prosodic differences in the utterances for three of the four signers, but that homesigners, unlike LSN signers, do not systematically shorten the verb in these embedded contexts. We consider other interpretations in the General Discussion.

Table 2
Temporal distance between verbs in two clauses across all conditions, in seconds.

	identifier+action	Sequential action	Repeated action
Homesigner 1	1.06	1.91	1.51
Homesigner 2	0.03	0.85	1.63
Homesigner 3	0.54	2.24	2.55
Homesigner 4	1.63	1.87	1.41

6. General discussion

In this study, we track the origins of recursion by studying users of a newly created language and people with no language model. Across three experiments, we sought to elicit sentences with relative clauses (sentences embedded within a noun phrase) and comparable sentences with conjoined verbs (which are not embedded) so that we could compare them. In the embedded contexts, LSN signers produced utterances with the content and function of relative clauses. Specifically, they often produced utterances in which an action that had already been described was mentioned again for the purpose of identifying the character who performed a second critical action. The form of these utterances suggested that they contained embedded predicates. Specifically, in the embedded contexts the first verb, the embedded verb, was shorter in duration than it was in the unembedded contexts. In unembedded contexts there was often a timing gap between the two verbs (due to a pause or other signs) while in the embedded contexts the gap between the two verbs was quite short. These prosodic changes were not due to an effect of repetition. We observed no shortening of the verb when it was repeated a second time in a non-embedded context. The shortening of the verb in the embedded and potentially recursive utterances became even more pronounced as the language developed, with younger signers producing shorter forms.

Homesigners showed a different pattern from the LSN signers. While the homesigners did produce descriptions that included both the identifying action and the new event, they did not describe the identifying action twice. Thus it is unclear whether the identifying verb is being used as a modifier or a predicate. Second, the identifying verb in these descriptions was not shortened relative to the first verb control utterances. However, in three of the four homesigners, we did find a more subtle prosodic difference between the conditions. The timing gap between the first verb and the second verb was shorter in the critical condition than in the control conditions.

In the remainder of the General Discussion, we discuss the following: the range of possible analyses for the pattern that we observed in the homesigners (section 6.1), alternative accounts how embedding might emerge in a new language (section 6.2), a discussion of the evidence for embedding and planned work for demonstrating recursion (section 6.3), an alternative analysis of these putative relative clauses as adjectives (section 6.4), possible analyses of the verb reduction observed in LSN (section 6.5), and the reconciliation of our findings with the case of Piraha (section 6.6). We end our discussion with some final words (section 6.7).

6.1. Three possible explanations for why we found no visible signs of embedding in homesign

Logically, there are three possible interpretations of the pattern that we observed in adult homesigners. We cannot rule out any of these hypotheses on the basis of the present data, but we favor the first hypothesis.

The first hypothesis is that the difference between homesigners and LSN users is simply a difference in the way in which they mark linguistic forms. Homesigners could have a conceptual system that allows them to build recursive thoughts and a syntactic system that allows them to produce embedded verbs, but they may not mark this distinction with verb reduction. There are two slightly different ways of conceptualizing the pattern that we see in LSN, which have different implications for our understanding of homesign.

On the one hand, we could think of verb shortening as a morphosyntactic device that serves as a categorical signal to embedding. On this construal, it is unsurprising the homesign lacks verb reduction. Languages vary in which syntactic distinctions are marked and how. This is true in sign languages as well as spoken languages. For example, while relative clauses in ASL can be marked with nonmanual markers, relative clauses in DGS are marked with a relative pronoun as well as an eyebrow raise. Each homesign system is an independent, evolving form of communication. Given the variability in how relative clauses are morphosyntactically marked in sign languages, we should expect variation both across homesign systems and between homesign and LSN. It is possible, for example, that some or all of the homesigners are marking embedded predicates through use of a different device (e.g., facial expressions) that is not explored in this paper.

On the other hand, verb reduction in LSN could be a direct reflection of the prosodic structure of the utterance. Since the prosodic form of an utterance is influenced by its syntactic form, we might expect verb length to vary depending on syntactic context. Specifically, the verb should be longer when it is at the edge of a major syntactic constituent (e.g., the end of a conjoined clause) and shorter when it is not. This could result in the systematic difference that we observed between embedded and unembedded verbs. On this construal, the absence of verb reduction in homesign would be more surprising: if homesigners are producing embedded structures (with the same linear order as the LSN sentences) then we might expect to see the same changes in prosody. In fact, our post-hoc analysis of the timing gap strongly suggests that the homesigners, like the LSN signers, are making a bigger prosodic break after the first verb in the control conditions (resulting in a longer timing gap). One way to reconcile this with the verb data is to posit that because homesign is slower and more effortful, prosodic breaks occurred in both types of utterances, but longer breaks occurred for the control utterances. The other path, is take this dissociation between verb reduction and the timing gap as evidence that shortening in LSN is in fact morphosyntactic rather than a side effect of prosody.

The second hypothesis is that homesigners have the relevant conceptual structures (embedded and potentially recursive) but lack the syntactic structures that would allow them to express these ideas. For example, perhaps the homesigners in the present study were able to conceive of a message in which the girl who had been drawing removed a picture, but they were not able to construct a grammatical representation in which a predicate could be embedded within a noun. Given this constraint, homesigners may have attempted to convey this message via parataxis, producing non-embedded sentences to express an embedded meaning. Such a data pattern would suggest a disconnect between the syntax of an external linguistic system and the representations available for internal thought. The challenge for this hypothesis is to explain why three of the four homesigners were more likely to produce the potentially embedded sentences with a smaller pause or gap than the unembedded controls. One could argue that this evidence is tentative: the analysis was post-hoc and forced us to compare different verbs and events. Subsequent work should seek to replicate these effects while controlling for the lexical content. An alternative possibility is that these differences in pause length do not reflect the syntactic structure but instead are non-syntactic side effects of the difference in conceptualization (e.g., maybe retrieving the second event is faster when there is embedding in the conceptual representation).

The third and final interpretation of this pattern is that homesigners lack the conceptual structures necessary to formulate messages with embedded meanings, as well as the syntactic structures needed to convey them. This hypothesis would be consistent with theories in which external language serves as the medium for complex combinatorial thought (Carruthers, 2002; de Villiers & de Villiers, 2014; Spelke, 2003; Xu, 2007). On this hypothesis, the message that the homesigners were conveying on the critical trials was not distinct from the message that they were conveying in the conjoined action trials: in both cases they were expressing that the girl drew and she removed the painting. We assume that they realized that she was the same girl and that this was relevant to the task (after all, two of the homesigners often mentioned her last) but that does not require formulating a thought in which there is an embedded conceptual representation.

While this third hypothesis is logically possible, we think that it is unlikely for several reasons. First, in this study and in prior work (Goldin-Meadow, 1982) some homesigners have produced strings that appear, to the researchers seeing them, to express embedded meanings in the contexts in which they are used. This is readily explained on either the first hypothesis (embedded meanings expressed with embedded structures) or the second (embedded meaning expressed via parataxis). On the third hypothesis, these observations would have to be dismissed as an illusion due to the presence of embedded conceptual structures in the observer.

Second, the third hypothesis is difficult to reconcile with the rapid emergence of embedded predicates in LSN. If homesigners do not represent these conceptual embeddings then how and why did the first cohort of LSN signers develop the capacity to think these thoughts? It is common to invoke the notion of communicative pressure to explain the creation of new linguistic structures. But why would there be pressure to express something that you cannot even think? And what would the building blocks be that would allow you to create embedded conceptual structures once that the pressure was applied but would fail to create these meanings otherwise? We cannot rule out this possibility but the explanatory burden would be heavy.

There is one facet of the data that favors the second hypothesis over the first. The homesigners, unlike the LSN users, did not describe all three characters before producing the critical utterance with two verbs. Instead they typically described only the critical character and used the identifying verb just once. Thus the use of the identifying action in their descriptions was different than the typical embedded predicate: it did not refer back to information that was already in the discourse in a manner that would be redundant if it were not embedded in the noun phrase and serving a referential function. This difference is easily explained if the homesigners do not have syntactic structures that would allow them to express embedded predicates and are thus forced to use parataxis to convey embedded meanings (the second hypothesis). Mentioning multiple characters makes it less likely that your interlocutor will correctly infer your intent. By describing just one girl the possibility of confusion is reduced. This finding is not as readily explained by the first hypothesis: if homesigners were producing embedded syntactic structures (either with a different marking or no marking at all), then we might expect, all other things being equal, that these structures would occur in the same discourse environments as embedded predicates in LSN and other languages.

Nevertheless, there are other plausible explanations for why homesigners might not establish the comparison set, and for this reason we cannot rule out the first hypothesis. First, homesigners are generally less fluent, mentioning fewer referents per minute, and thus there is a bigger cost, in terms of time, for the producer to describe all members of the set. This could be due to pragmatic differences (Gagne & Coppola, 2017), differences in their phonological language production system, or because their lexicons are less stable (Richie, Yang, & Coppola, 2014) and thus clearly identifying each referent may take longer. Second, because homesigners primarily communicate with hearing family members, they may have adapted to less fluent comprehenders who are likely to become confused by more information. This might lead them to carefully focus their message on the most relevant information. Indeed, Carrigan and Coppola (2017) demonstrate that homesigners' mothers show relatively poor comprehension of homesign productions. Third, to be able to compare the homesign and LSN data, we used the same elicitation methods with homesigners as with LSN signers, in which participants were simply asked to describe what happened. It is possible that homesigners construed the task in a different way, leading them to see the other characters as irrelevant.

These findings motivate future research on: the ability of

homesigners to represent conceptual embedding in nonlinguistic tasks, their understanding of their own productions (do they distinguish the strings produced in embedded and unembedded contexts?), and their ability to convey other potentially recursive content (e.g., sentence complements, compound nouns, or hierarchically applied adjectives).

6.2. Possible external sources of embedded structures and arguments against

We observed embedded utterances, with verb shortening, in signers from the first three cohorts of LSN. These findings suggest that systematic linguistic encoding of embedded meanings arises very rapidly in the creation of a new language. The contrast between LSN and homesign suggest that recursive structures may be systematized shortly after a linguistic community, with multiple speakers, comes together. While there was a great deal of individual variation in homesigners' utterances, some produced meanings that appeared to be embedded. Such utterances may have served as input to the first group of signers who reanalyzed and restructured the developing language. Taken at face value, these results suggest that embedded conceptual structures are a property of the human mind that can rapidly give rise to embedded linguistic structures when people come together and communicate.

However, there is one possible alternative explanation for the origin of these structures in LSN: perhaps they were borrowed from an existing language, such as Spanish, the language of the surrounding community. If borrowing of this kind occurred, then we would expect that the form of relative clauses in LSN would mirror that of the source language. We do not see this. Spanish marks relative clauses with relative pronouns, which we did not observe in LSN. Furthermore, LSN appears to be marking relative clauses with a reduction in the verb, which neither Spanish nor ASL does. There is however, a more subtle and plausible version of this hypothesis. Perhaps exposure to a language that has recursive structure made the concepts encoded by these rules more salient to LSN users, which then hastened the emergence of recursive language. While we cannot rule out this possibility, we note one theoretical limitation. This hypothesis either requires that LSN users already had internal representations of embedding or it requires an explanation of how they were able to map external representations with embedding (in Spanish) onto mental representations (linguistic or conceptual) that did not have that form.

Another possibility is that these embedded structures emerged later in the language and were adopted by the first cohort. Future work will explore historical data for evidence of these structures. One critical source of evidence against this possibility comes from an earlier study by Kegl and Stickney (2002) that elicited relative clauses from six LSN signers. A close examination of one signer who entered the community in 1989 (a second-cohort signer) revealed use of structures that appeared to serve the function of relative clauses as well as a possible nonmanual marker for relative clauses. These findings suggest that relative clauses appeared to be present in the language at an earlier time point.

6.3. Evidence for embedding but not (yet) recursion

Throughout this paper, we have referred to the steps outlined in the Introduction that are necessary to demonstrate that a language has a particular device, such as recursion. Step 1 involves identifying strings with the relevant meaning, ideally via elicitation so that the meaning can be evaluated independently of the string itself. Step 2 involves demonstrating systematic differences between these strings and parallel strings with non-embedded meanings. Step 3 includes ruling out alternative analyses via elicitation of a variety of embedded and non-embedded control utterances, including utterances with multiple embeddings to demonstrate that these structures are truly recursive.

Prior studies have made headway on Step 1, by identifying potential examples of relative clauses (or other cases of embedding) in homesign (Goldin-Meadow, 1982) and emerging sign languages (Kastner et al., 2014; Dachkovsky, 2017; Kegl & Stickney, 2002).

In the present study, we tackled Step 2, by systematically varying the context so we could compare potentially embedded utterances with matched utterances without the embedding, in order to determine whether there are systematic differences between them. We found that the embedded clauses differed from the unembedded clauses in three respects. First they were redundant in their content, unless they were semantically interpreted as embedded within the subject noun phrase (semantic embedding). Second, the form of the verb in the embedded clause was shorter compared to non-embedded clauses, which is what we would expect if these structures are relative clauses. Third, while there was often a gap between the two verbs in the unembedded contexts, the gap was shorter or absent when the first verb was embedded.

With these data, we are now in a position to begin Step 3 and assess whether these embedded structures are truly recursive. More concretely, our next steps include, but are not limited to: elicitation of utterances with multiple levels of embedding, elicitation of relative clauses that attach to different nouns in the main clause (subject vs. object), and elicitation of relative clauses in which the gap is in different places in the embedded clause (subject vs. object). We also plan to use the utterances that we elicit in comprehension studies to determine whether listeners can reliably distinguish embedded structures and interpret the intended meaning. In addition, future work should also examine existing historical data from the 1990s to determine whether we can find evidence of these structures at an earlier point in the language.

As we did not elicit utterances with more than one level of embedding, we cannot yet say whether LSN signers can embed a sentence within a sentence within a sentence. However, there are reasons to believe that self-embedding provides prima facie evidence for structural recursion. Even in a mature language, multiple levels of embedding are uncommon except in written texts (Karlsson, 2007). For this reason, children are presumed to learn recursive rules from examples with a single level of embedding (Lightfoot, 1989). In fact, a grammar that allows for self-embedding without recursion requires more rules, or more complex rules, than a recursive system (see e.g., Perfors, Tenenbaum, & Regier, 2011).

6.4. Alternative analysis: adjectives, not verbs

There is an alternative analysis of the embedded verbs in the identifier+action trials: rather than being the main verb of a relative clause, they might instead be deverbal adjectives. These are verbs that are used as adjectives, as in "The drawing [girl] removed the picture". This alternative analysis still involves embedding (since the deverbal adjective is embedded in the NP), but it might not involve recursion (that would depend on the categories we assign to each of these constituents).

Further work needs to be done to test this possibility. Note that making this distinction is not trivially easy. While English uses different strategies, not all languages have dedicated morphosyntactic constructions for adjectives and relative clauses (Gil, 2013). Some languages, such as Tagalog, use the same strategy to mark both constructions.

Nevertheless, it is worth noting that the strings that we observed are precisely the kind of strings that Everett (2005) looked for and failed to find in Pirahã and that Futrell et al. (2016) searched for in their corpus analysis. These are also precisely the kinds of strings that language acquisition researchers have used to argue for the presence of relative clauses in young children (e.g., McKee et al., 1998). Given that we were able to find such strings in the initial investigation of recursion in LSN, we are now in position to probe these structures further. In future work, we can apply more stringent tests to determine the structure of these strings (e.g., syntactic tests involving quantifiers) and ask whether multiple levels of embedding are possible (see section 6.3).

The present study is a critical step in addressing this question. These findings demonstrate that we can elicit strings which serve the discourse function of a relative clause, that have an embedded meaning (an event

with a participant that is distinguished by virtue of being in another event), and that show a hallmark of linguistic embedding (reduction). We can now ask more about how these strings are constructed and interpreted (Step 3).

6.5. The reduction of the verb

There are at least three ways of interpreting the reduction in the verb that we observe in the embedded contexts. First, the reduction could be a direct encoding of the syntactic structure. Second, it could be an indirect effect of syntax on the prosodic structure of the utterance. Third, the reduction could reflect the discourse status of the embedded predicate. Below, we consider each of these hypotheses in turn, and the predictions that they make for future research.

The syntactic hypothesis seems, at first glance, to be an unlikely one. On this account verb reduction is a syntactic feature that distinguishes embedded verbs from matrix verbs. This kind of rule would be unusual: part of the rationale for claiming embedded clauses are recursive is that they generally follow the same rules as matrix clauses and thus it is most parsimonious to assume that they have the same morphosyntactic properties as other clauses. Nevertheless, there are clearly cases where matrix and embedded clauses behave differently. For example, in many Germanic languages, the matrix verb occurs as the second constituent of the sentence, while embedded verbs are clause final. If this is the case, we would expect to see a shortening of embedded verbs across different embedded syntactic contexts. Note that languages vary in which structures are recursive. Possessives are recursive in English and Japanese, but not German; compounds tend to be recursive in Germanic languages, but not Romance languages. Prenominal adjectives are recursive in English but not post-nominal adjectives and French shows the opposite pattern (Roeper, 2011). As such, future work is needed to identify which structures can be embedded and are recursive in LSN and whether the embedded elements exhibit this reduction in the length of the sign.

A second hypothesis is that the reduction is an indirect byproduct of embedding. On this hypothesis, verb reduction is not a direct marker of embedding but instead reflects general principles of the syntax/prosody interface. There is a large body of research demonstrating that there are systematic links between the syntactic structure of an utterances and its prosodic structure (e.g., Féry & Schubö, 2010; Féry, 2011; Kubozono, 1989; Ladd, 1986; Wagner, 2010). On the strongest version of this hypothesis, there is a direct isomorphism between prosody and syntax, with prosody having a recursive hierarchical structure derived from the hierarchical structure of the syntactic tree (e.g., Elfner, 2015; Ito & Mester, 2013; Selkirk, 2009, 2011). In other theories, prosodic structures themselves are not recursive, but recursive syntactic structures place constraints on intonational phrasing that result in different prosodic structures for a constituent depending on how deeply it is embedded (Watson & Gibson, 2004; Wagner, 2010; Snedeker & Casserly, 2010). In some cases, these constraints result in embedded phrases being produced more rapidly and with less emphasis (e.g., Snedeker & Trueswell, 2004).

A third analysis is that the syntactic structures of embedded and non-embedded clauses are the same in LSN, but the discourse function of relative clauses results in a different prosodic realization compared to non-embedded clauses, leading verbs to be reduced in length. Relative clauses function to pick out a referent from a set of alternatives. As such, a sentence containing a relative clause frequently expresses information that has already been mentioned, and thus is old, followed by information that is new. As an example, in our elicited sentences containing relative clauses, the first verb (in the putative relative clause) picked out a previously-mentioned individual (e.g., the girl who was drawing) and the second verb (in the matrix clause) predicated something new of that individual (e.g., removed the painting). On this analysis, the shortening of the second mention of the identifying verb is driven by its information status (old/given information) and we should expect to see this shortening anytime the verb expresses information that has already been mentioned in the discourse, both in embedded and non-embedded contexts. As relative clauses almost always express old/given information, information status is perfectly confounded. As such, future work with different syntactic structures is needed to test this analysis.

In this section, we have put forth and discussed three possible analyses for the reduction of the verb we observed in our embedded and potentially recursive structures. Because we were able to identify utterances with the relevant embedded meanings and compare them with utterances with non-embedded meanings (Steps 1 and 2), we are now in the position to take Step 3, conducting the necessary studies to sort through these alternative analyses by eliciting a variety of embedded (and unembedded) utterances.

6.6. The case of Pirahã

There are at least three possible explanations to reconcile our findings of early emergence of embedded and potentially recursive structures in LSN with the proposals that Pirahã lacks sentential embedding. We consider each of these explanations below.

The first possible explanation for these different sets of findings is that recursive rules may indeed be absent in Pirahã. Pirahã may represent the boundary case in which all potentially recursive rules are absent. Alternatively, perhaps recursive structures existed previously in the language and disappeared. While studying other languages cannot directly address this possibility, such data would allow for a better picture of the range of possible diversity of recursive rules in languages.

A second explanation rests on recognizing that Everett's (2005) claim about Pirahã is controversial. The purported absence of recursion in Pirahã has generated a great deal of attention and discussion in the literature (e.g., Amaral, Maia, Nevins, Roeper, & Eds.)., 2018; Everett, 2005; Futrell et al., 2016; Nevins et al., 2009; Rodrigues, Salles, & Sandalo, 2018; Sauerland, 2015). Futrell et al. (2016) failed to find clear evidence for recursive embedding in a corpus analysis of Pirahã. Others, however, have proposed alternative analyses (e.g., Nevins et al., 2009; Rodrigues et al., 2018; Sauerland, 2015 but see Everett & Gibson, 2019). Nevins et al. (2009) apply a different definition of recursion, Merge, arguing that as Pirahã has the capacity to form sentences with two or more words, the language has recursion (Merge can be applied iteratively, taking its own output as input, to form larger structures; thus the rule is said to be recursive). In an experiment looking at false speech reports, Sauerland (2015) argues that Pirahã has a complementizer that marks embedded clauses (but see Everett & Gibson, 2019 for an alternative interpretation of this finding). What is clear from this body of work is that the debate around recursion in Pirahã is far from settled. Additional data from understudied languages would be informative in addressing some concerns raised in and about these proposals.

Third, methodological differences may underlie these divergent findings. The analyses of Pirahã are based on corpus data and informal elicitation. In part because there is no corpus of LSN available, we devised contexts that allowed us to elicit and compare utterances produced in embedded contexts and minimally different non-embedded contexts. This allowed us to elicit utterances containing strings that were good candidates for embedded and potentially recursive utterances and whose meaning could be evaluated independently of the potentially recursive structure itself. Given the challenges of working with corpus data, it is possible that if similar elicitation contexts were used with Pirahã speakers, researchers would be in a better position to find evidence of sentential embedding in the language, if it exists. At the very least, the use of elicitation contexts is an interesting possible avenue for future work on Pirahã.

6.7. Final words

This study provides empirical evidence that embedded predicates, resulting in potentially recursive structures, appear quickly in an emerging language, suggesting that embedding of this kind is a robust

property of the human mind. Individual homesign utterances conveying embedded meanings likely served as input to an initial group of signers, and embedded structures may have emerged as these child learners reanalyzed each others' utterances. Potentially recursive language can apparently arise as soon as children form a language community, restructuring their language together to create new linguistic resources.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2022.105261.

References

Amaral, L., Maia, M., Nevins, A., & Roeper, T. (Eds.). (2018). *Recursion Across Domains*. Cambridge University Press.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*, 390–412.

Bates, D., Mächler, M., Bolker, B., & Walker, S. *Fitting linear mixed-effects models using lme4. arXiv preprint.* (2014). arXiv:1406.5823.

Boyer, C. B., & Merzbach, U. C. (2011). *A history of mathematics*. Hoboken, NJ: John Wiley & Sons.

Brentari, D., & Coppola, M. (2012). What sign language creation teaches us about language. *Wiley Interdisciplinary Reviews, Cognitive Science (WIREs)*. https://doi.org/10.1002/(ISSN)1939-5086

Carrigan, E. M., & Coppola, M. (2017). Successful communication does not drive language development: Evidence from adult homesign. *Cognition, 158*, 10–27.

Carruthers, P. (2002). The cognitive functions of language. *Behavioral and Brain Sciences, 25*(6), 657–674. https://doi.org/10.1017/s0140525x02000122

Chomsky, N. (1980). *Rules and representations*. New York: Columbia University Press.

Comrie, B., & Kuteva, T. (2013). Relativization on obliques. In *The world atlas of language structures online*.

Coppola, M., & Senghas, A. (2010). Deixis in an emerging sign language. In D. Brentari (Ed.), *Sign languages: A Cambridge language survey* (pp. 543–569). Cambridge: Cambridge University Press.

Coulter, G. R. (1993). Phrase-level prosody in ASL: Final lengthening and phrasal contours. In G. R. Coulter (Ed.), *Phonetics and Phonology, Volume 3: Current Issues in ASL Phonology* (pp. 263–272). San Diego: Academic Press.

Dachkovsky, S. (2017). *Grammaticalization of intonation in Israeli sign language*. Doctoral dissertation. Haifa, IL: University of Haifa.

de Villiers, J. G., & de Villiers, P. A. (2014). The role of language in theory of mind development. *Topics in Language Disorders, 34*(4), 313–328. https://doi.org/10.1097/TLD.0000000000000037

Deutscher, G. (2000). *Syntactic change in Akkadian: The evolution of sentential complementation*. New York: Oxford University Press.

Elfner, E. (2015). Recursion in prosodic phrasing: Evidence from Connemara Irish. *Natural Language & Linguistic Theory, 33*, 1169–1208.

Emmorey, K. (2002). *Language, cognition, and the brain: Insights from sign language research*. Hillside, NJ: Erlbaum.

Engberg-Pedersen, E. (1993). *Space in Danish sign language: The semantics and morphosyntax of the use of space in a visual language*. Hamburg Germany: Signum Press.

Ergin, R. (2017). *Central Taurus Sign Language: A Unique Vantage Point Into Language Emergence*. Doctoral dissertation. Tufts University.

Everett, D. (2005). Cultural constraints on grammar and cognition in Pirahã: Another look at the design features of human language. *Current Anthropology, 76*, 621–646.

Everett, D. L., & Gibson, E. (2019). Recursion across domains. ed. by Luiz Amaral et al. (review). *Language, 95*(4), 777–790.

Fenlon, J., Denmark, T., Campbell, R., & Woll, B. (2007). Seeing sentence boundaries. *Sign Language & Linguistics, 10*(2), 177–200. https://doi.org/10.1075/sll.10.2.06fen

Féry, C. (2011). German sentence accents and embedded prosodic phrases. *Lingua, 121*, 1906–1922.

Féry, C., & Schubö, F. (2010). Hierarchical prosodic structures in the intonation of center-embedded relative clauses. *The Linguistic Review, 27*, 293–317.

Futrell, R., Stearns, L., Everett, D. L., Piantadosi, S. T., & Gibson, E. (2016). A corpus investigation of syntactic embedding in Pirahã. *PLoS One, 11*, Article e0145289.

Gagne, D. (2015). *Theory of mind without a language model: Effects of social experience, education and language exposure*. Storrs, CT: University of Connecticut Masters Thesis.

Gagne, D. L. (2017). With a little help from my friends: The contributions of a peer language network on the conventionalization of space in an emerging language. Doctoral dissertation https://opencommons.uconn.edu/dissertations/1493.

Gagne, D. L., & Coppola, M. (2017). Visible social interactions do not support the development of false belief understanding in the absence of linguistic input: Evidence from deaf adult homesigners. *Frontiers in Psychology, 8*, 837.

Gil, D. (2013). Genitives, adjectives and relative clauses. In Matthew S. Dryer, & Haspelmath Martin (Eds.), *The world atlas of language structures online*. Leipzig: Max Planck Institute for Evolutionary Anthropology. (Available online at http://wals.info/chapter/60 Accessed on 2022-09-08.).

Goldin-Meadow, S. (1982). The resilience of recursion: A study of a communication system developed without a conventional language model. In E. Wanner, & L. R. Gleitman (Eds.), *Language acquisition: The state of the art*. New York: Cambridge University Press.

Green, K. (1984). Sign boundaries in american sign language. *Sign Language Studies, 42*, 65–91.

Hamburger, H., & Crain, S. (1982). Relative acquisition. In S. Kuczaj (Ed.), *Language development: Syntax and semantics* (pp. 245–274). Hillsdale, NJ: L. Erlbaum.

Hauser, M. D., Chomsky, N., & Fitch, W. T. (2002). The faculty of language: What is it, who has it, and how did it evolve? *Science, 298*, 1569–1579.

Hou, L. (2018). Iconic patterns in San Juan Quiahije Chatino Sign Language. *Sign Language Studies, 18*(4), 570–611.

Ito, J., & Mester, A. (2013). Prosodic subcategories in Japanese. *Lingua, 124*, 20–40.

Karlsson, F. (2007). Constraints on multiple center-embedding of clauses. *Journal of Linguistics, 43*, 365–392.

Kastner, I., Meir, I., Sandler, W., & Dachkovsky, S. (2014). The emergence of embedded structure: Insights from Kafr Qasem sign language. *Frontiers in Psychology, 5*, 1–15.

Keenan, E. L. (1985). Relative clauses. *Language Typology and Syntactic Description, 2*, 141–170.

Kegl, J., & Iwata, G. (1989). Lenguaje de Signos Nicaragüense: A pidgin sheds light on the "creole?". In R. Carlson, S. DeLancey, S. Gilden, D. Payne, & A. Saxena (Eds.), *Proceedings of the fourth annual meeting of the Pacific linguistics conference* (pp. 266–294). Eugene: University of Oregon, Department of Linguistics.

Kegl, J., & McWhorter, J. (1997). Perspectives on an emerging language. In *Proceedings of the StanfordChild Language Research Forum* (pp. 15–36). Palo Alto: Center for the Study of Language and Information.

Kegl, J., Senghas, A., & Coppola, M. (1999). Creation through contact: Sign language emergence and sign language change in Nicaragua. In M. DeGraff (Ed.), *Language creation and language change: Creolization, diachrony, and development* (pp. 179–237). Cambridge: MIT Press.

Kegl, J., & Stickney, H. (2002). *Relative Clauses in Nicaraguan Sign Language*. San Francisco, CA: Poster presented at the Linguistics Society of America Meeting. January 3-6.

Kubozono, H. (1989). Syntactic and rhythmic effects on downstep in Japanese. *Phonology, 6*, 39–67.

Ladd, D. R. (1986). Intonational phrasing: The case for recursive prosodic structure. *Phonology, 3*, 311–340.

Lausberg, H., & Sloetjes, H. (2009). Coding gestural behavior with the NEUROGES-ELAN system. *Behavior Research Methods, Instruments, & Computers, 41*, 841–849.

Liddell, S. K. (1978). Nonmanual signals and relative clauses in American Sign Language. In P. Siple (Ed.), *Understanding language through sign language research* (pp. 59–90). New York: Academic Press.

Liddell, S. K. (1980). *American sign language syntax* (Vol. 52). Mouton De Gruyter.

Lightfoot, D. (1989). The child's trigger experience: Degree-0 learnability. *Behavioral and Brain Sciences, 12*, 321–334.

McBurney, S. L. (2002). Pronominal reference in signed and spoken language: Are grammatical categories modality-dependent. In *Modality and structure in signed and spoken languages* (pp. 329–369).

McKee, C., McDaniel, D., & Snedeker, J. (1998). Relatives children say. *Journal of Psycholinguistic Research, 27*(5), 573–596.

Meier, R. P. (1990). Person deixis in American sign language. *Theoretical Issues in Sign Language Research, 1*, 175–190.

Nevins, A., Pesetsky, D., & Rodrigues, C. (2009). Pirahã exceptionality: A reassessment. *Language, 85*, 355–404.

Padden, C. (1988). *Interaction of morphology and syntax in American sign language*. New York: Garland Publishers.

Parker, A. R. (2006). Evolving the narrow language faculty: was recursion the pivotal step? In Angelo Cangelosi, Andrew D. M. Smith, & Smith Kenny (Eds.), *The Evolution of Language: Proceedings of the 6th International Conference (Evolang 6)* (pp. 239–246). London: World Scientific.

Perfors, A., Tenenbaum, J. B., & Regier, T. (2011). The learnability of abstract syntactic principles. *Cognition, 118*, 306–338.

Pfau, R., & Steinbach, M. (2005). Relative clauses in German sign language: Extraposition and reconstruction. *Proceedings of the North East Linguistic Society, 35*, 507–521.

Pinker, S., & Jackendoff, R. (2005). The faculty of language: What's special about it? *Cognition, 95*, 201–236.

Polich, L. (2005). *The emergence of the deaf community in Nicaragua: With sign language you can learn so much*. Washington DC: Gallaudet University Press.

Richie, R., Yang, C., & Coppola, M. (2014). Modeling the emergence of lexicons in homesign systems. *Topics in Cognitive Science, 6*, 183–195.

Rodrigues, C., Salles, R., & Sandalo, F. (2018). *Word order in control: Evidence for self-embedding in Pirahã*.

Roeper, T. (2011). The acquisition of recursion: How formalism articulates the child's path. *Biolinguistics, 5*, 57–86.

Sampson, G. (2009). A linguistic axiom challenged. In G. Sampson, D. Gil, & P. Trudgill (Eds.), *Language complexity as an evolving variable* (pp. 1–18). Oxford: Oxford University Press.

Sandler, W., & Lillo-Martin, D. (2006). *Sign Language and Linguistic Universals*. Cambridge: Cambridge University Press.

Sandler, W., Meir, I., Padden, C., & Aronoff, M. (2005). The emergence of grammar: Systematic structure in a new language. *Proceedings of the National Academy of Sciences, 102*(7), 2661–2665. https://doi.org/10.1073/pnas.0405448102

Sauerland, U. (2015). False speech reports in Pirahá: A comprehension experiment. In L. Amaral, M. Maia, A. Nevins, & T. Roeper (Eds.), *Recursion and embedding in Brazilian languages and beyond*. Cambridge University Press:21–34.

Selkirk, E. (2009). On clause and intonational phrase in Japanese: The syntactic grounding of prosodic constituent structure. *Gengo Kenkyu, 136*, 35–73.

Selkirk, E. (2011). The Syntax-Phonology Interface. In J. Goldsmith, J. Riggle, & A. Yu (Eds.), *The Handbook of Phonological Theory* (2nd edition, pp. 435–484). Oxford: Blackwell Publishing.

Senghas, A. (1995). *Children's contribution to the birth of Nicaraguan sign language*. Doctoral dissertation. Cambridge MA: MIT.

Senghas, A. (2005). Language emergence: Clues from a new Bedouin sign language. *Current Biology, 15*(12), 463–465.

Senghas, A., & Coppola, M. (2001). Children creating language: How Nicaraguan sign language acquired a spatial grammar. *Psychological Science, 12*, 323–328.

Senghas, A., Kita, S., & Özyürek, A. (2004). Children creating core properties of language: Evidence from an emerging sign language in Nicaragua. *Science, 305*, 1779–1782.

Senghas, R. J., Senghas, A., & Pyers, J. E. (2005). The emergence of Nicaraguan sign language: Questions of development, acquisition, and evolution. In *Biology and knowledge revisited: From neurogenesis to psychogenesis* (pp. 287–306).

Snedeker, J., & Casserly, E. (2010). Is it all relative? Effects of prosodic boundaries on the comprehension and production of attachment ambiguities. *Language & Cognitive Processes, 25*, 1234–1264.

Snedeker, J., & Trueswell, J. (2004). The developing constraints on parsing decisions: The role of lexical biases and referential scenes in child and adult sentence processing. *Cognitive Psychology, 49*, 238–299. https://doi.org/10.1016/j.cogpsych.2004.03.001

Snyder, W. (2001). On the nature of syntactic variation: Evidence from complex predicates and complex word-formation. *Language, 77*(2), 324–342. https://www.jstor.org/stable/3086777.

Spelke, E. S. (2003). What makes us smart? Core knowledge and natural language. In D. Gentner, & S. Goldin-Meadow (Eds.), *Language in mind: Advances in the study of language and thought* (pp. 277–311). Cambridge, MA: MIT Press.

Steels, L. (2016). Agent-based models for the emergence and evolution of grammar. *Philosophical Transactions of the Royal Society B, 371*, 20150447.

Sutton-Spence, R., & Woll, B. (1999). *The Linguistics of British Sign Language: An Introduction*. Cambridge: Cambridge University Press.

Wagner, M. (2010). Prosody and recursion in coordinate structures and beyond. *Natural Language & Linguistic Theory, 28*(1), 183–237.

Watson, D., & Gibson, E. (2004). The relationship between intonational phrasing and syntactic structure in language production. *Language & Cognitive Processes, 19*, 713–755.

Wittenburg, P., Brugman, H., Russel, A., Klassmann, A., & Sloetjes, H. (2006). ELAN: A professional framework for multimodality research. In *Proceedings of LREC 2006, Fifth international conference on language resources and evaluation*.

Woll, B., Sutton-Spence, R., & Elton, F. (2001). Multilingualism: The global approach to sign languages. *The sociolinguistics of sign languages, 8*, 32.

Xu, F. (2007). Sortal concepts, object individuation, and language. *Trends in Cognitive Science, 11*(9), 400–406. https://doi.org/10.1016/j.tics.2007.08.002