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Distinguishing selection pressures in an evolving communication system: Evidence from color-naming in "cross signing"

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Cross-signing—the emergence of an interlanguage between users of different sign languages—offers a rare chance to examine the evolution of a natural communication system in real time. To provide an insight into this process, we analyse an annotated video corpus of 340 minutes of interaction between signers of different language backgrounds on their first meeting and after living with each other for several weeks. We focus on the evolution of shared color terms and examine the role of different selectional pressures, including frequency, content, coordination and interactional context. We show that attentional factors in interaction play a crucial role. This suggests that understanding meta-communication is critical for explaining the cultural evolution of linguistic systems.

KEYWORDS

cross-signing, International Sign, interaction, cultural evolution, selection, content bias, coordination bias, conformity bias

Introduction

The survival of a cultural trait depends on it being transmitted successfully from person to person (Laland, 2004; Boyd and Richerson, 2005; Kendal et al., 2018). Various *transmission biases* are thought to affect the process (see Boyd and Richerson, 1988; Henrich, 2001) such as the inherent "effectiveness" of the variant (content bias), but also a bias for people to adopt the most frequent variant (frequency or conformity bias) or variants used by others (coordination bias). Understanding these biases is critical to understanding how cultural systems change over time, including inferring cultural traits in the deep past and short-term changes in the present. Evidence for transmission biases have been demonstrated in various domains such as technology (Basalla, 1988; Buckley and Boudot, 2017), beliefs (Cavalli-Sforza et al., 1982) and storytelling (Stubbersfield et al., 2015). Language is another type of cultural phenomenon, and linguistic signals (words, signs) are also traits that evolve according to cultural transmission (Croft, 2000).

However, transmission biases in language may be subject to additional effects from communicative interaction. Furthermore, biases are not straightforward to test directly in language, since changes to established languages in some domains such as grammar can take a long time. Previous research has used "model systems" such as Twitter (Bryden et al., 2013; Tamburrini et al., 2015) and *experimental semiotics*: a controlled experiment where participants use a novel communication system that can evolve rapidly (see Caldwell and Millen, 2008; Galantucci and Garrod, 2011; Roberts, 2017).

While these methods provide experimental control, they often have low ecological validity. Linguistic signals have evolved primarily in a context of interactive, real-time, face-to-face conversation (Croft, 2000; Levinson, 2006; Enfield, 2014), not in these constrained model systems. However, the current understanding of the relationship between interactive elements and transmission biases is limited (see Enfield, 2014; Roberts and Mills, 2016). For example, different types of conversational turns execute different pragmatic actions, so that a phrase used in one context might carry more weight or mean something very different from it being used in another context (see Austin, 1976; Levinson, 2013; Gisladottir et al., 2015; Byun et al., 2018). Turns are also interrelated: types of turn make certain responses relevant and problems in understanding can be fixed in "repair" sequences (Schegloff et al., 1977; Dingemanse et al., 2015; Manrique, 2016). Therefore, it seems reasonable to expect that interactive structures may affect transmission.

To our knowledge there are no prior experimental studies focused on how the structure of conversation influences transmission in relation to other transmission biases. In order to investigate this, a setting is required that mimics the controlled conditions of experimental semiotics while allowing the flexibility and ecological validity of naturalistic conversation. There are several experimental studies where hearing adults use sign and gesture as a novel communication medium in order to study how communicative conventions emerge (see Motamedi et al., 2019). Some of these studies also consider interactional effects (e.g., Micklos, 2016), though none study transmission biases and interaction at the same time, and they rely on artificial experimental constraints to motivate the need for a novel communication system. There are also observational studies of real signed languages that emerge spontaneously. For example, Nicaraguan Sign Language, which emerged over the course of several decades in a deaf school (Senghas and Coppola, 2001), as well as in multiple "deaf villages" where a local sign language has emerged from the interaction of deaf and hearing community members (Meir et al., 2010; Zeshan and De Vos, 2012). However, these studies are often not designed to be experimentally controlled, and rarely capture the very first period of the emergence of a signed language. Another parallel is found in translanguaging situations where deaf and hearing people interact using various semiotic resources, including a shared gestural repertoire, a common cultural background, and in some cases a shared written language (Kusters, 2019).

One potential innovative approach is to study *cross-signing*. This is a naturally occurring context in which native users of different sign languages need to communicate with each other for the first time (see e.g., Zeshan, 2015; Kusters, 2021). In this study we combine the control of experimental semiotics with the ecological validity of cross-signing in order to assess the relative contribution of different biases to the emergence of a shared lexicon. We recreated the context for cross-signing to emerge in a lab by flying deaf individuals from Nepal, Jordan and Indonesia to India to live together for 3 weeks. Nepali Sign Language, Indian Sign Language, Jordanian Sign Language and Indonesian Sign Language are mutually unintelligible. None of the signers knew any of the other languages, and all reported having no international experience. They also reported that they did not know International Sign, i.e., which is distinct from the *ad hoc* form of signing we study here in terms of its longstanding tradition and community of users in international deaf contexts (though some of the features of their communication suggest that they may have had some experience of IS). Recordings were made of a structured communication task, based on communicating about colors. The domain of color was chosen because it was constrained enough to study individual variants, the concepts could be represented directly and easily to the participants (through color chips), it provided enough scope for ambiguity and different communication strategies including iconicity and it is also used in similar experiments in the cultural evolution literature (e.g., Berlin and Kay, 1969; Steels and Belpaeme, 2005; Morin et al., 2018). In this task, two signers were each given a cartoon image which differed only in the way certain objects were colored. They could not see their partner's image. Their task was to identify the differences in color by communicating spontaneously face-to-face. We coded and examined the signed variants used by the participants. The pairs participated in this task on their first meeting, then again after 1 week, and after 3 weeks, resulting in a 320-min video corpus, of which the initial and final meetings are reported on in this study as a subset of the data. This enabled us to quantify, examine and compare the production of certain forms and utterances robustly to determine what had changed or developed across the 3-week period.

Participants initially used a range of strategies, including pointing, articulating signs for common objects with that color, and their own native variants. However, after 3 weeks a consensus had been formed. For example, everyone used the Indian signer's variant for "green" and the Nepali signer's improvised "tree-trunk" variant for "brown".[1] Sequential analyses of the moment-by-moment interaction indicate that

1 We use color concepts with single quotes and capitalized letters to refer to specific sign variants.

signers continuously assessed the relative ease with which their forms might be understood, and adopted interactional strategies (e.g., try-marking, repair sequences) to manage communicative difficulties that arise. This allows us to quantify the effects for frequency, content and coordination biases, and how they are altered by the interactional context in which a form was used. To be clear, our focus is explaining which sign variants were replicated and preserved ("selected") over the 3 weeks as a model system for studying general, ongoing cultural evolution dynamics, rather than explaining the motivation of the variants themselves or as an analog of the origins of language.

Before explaining the study in detail, Section Color terms in signed languages summarizes what is known of expressions of color in signed languages, which will be instrumental in describing the strategies cross-signers adopted in this task. Section Biases in the cultural evolution of expressive forms details the hypotheses tested in this chapter on the basis of prior literature, including but not restricted to experimental semiotics. The remainder of this chapter is structured as follows: Section Methods describes the methods used in the study, including details about the participants, experimental procedure, transcription process, and statistical analysis. Section Results explains the results, and Section Discussion is a discussion of what the results indicate in terms of different biases. Finally, Section Conclusion brings the paper to a conclusion and suggests wider implications for language evolution research.

Color terms in signed languages

One of the reasons for selecting color as the target domain is that it lends itself to various iconic motivations for signs (Sagara and Zeshan, 2016). For this reason, the domain of color, shows considerable language-internal lexical variation across signed languages (Sagara and Zeshan, 2016). This variation can sometimes be quite extensive; for example, BSL has 22 signs for "purple" (Stamp, 2013). The size of the color sign inventory differs across languages, and may be influenced by social factors. The patterns of rural sign languages (aka village or emerging sign languages) are also relevant to cross-signing research because rural sign languages tend to be more context-dependent, smaller-scale sign languages with fewer lexical signs for colors, and more reliance on index pointing (cf. Meir et al., 2010; De Vos and Zeshan, 2012). Because the users of these sign languages live in smaller communities, they are under less pressure to devise lexical means of indicating colors (De Vos, 2011). This is similar to the situation of cross-signers, who also exploit pointing to a large extent. However, rural signers tend to know each other whereas cross-signers by definition do not. So, there are many aspects of the shared context that rural signers can draw on, including a shared community history and language and familiarity with each other, while for cross-signers the contextual sharedness is restricted to the immediate setting and the general patterns of human communication (cf. Mudd et al., 2022).

Berlin and Kay's (1969) seminal study looked at basic color terms across spoken languages. In their definition, basic color terms are monolexemic, perceptually and socially salient, not hyponyms (as in "crimson" is a hyponym for "red") and not contextually restricted (as in "blonde" which can only refer to hair or beer). English has 11 basic colors, but other languages in their sample had as few as three. Berlin and Kay showed that spoken languages have basic color terms according to an implicational hierarchy (the existence of a distinction implies all distinctions to the left): black/white $<$ red $<$ yellow/green $<$ blue $<$ brown $<$ other colors (later work established that other emerging patterns also occur, q.v. Kay and Maffi, 1999). That is, if they have a basic color term for red hues, then they will have one for black and white, and if they have basic color terms for yellow and green, then they will have one for red etc. Berlin and Kay hypothesized that this was also the order in which basic color terms evolve in a language (black and white first, then red, etc.).

Notably, in sign languages very few color signs adhere to the criteria for "basic colors" because of their iconic or indexical nature (e.g., pointing to exemplars) but nevertheless, Berlin and Kay's implicational hierarchy appears to be applicable to sign language typology as well. That is to say, Sagara and Zeshan (2016) show that emerging rural sign languages such as Adamorobe Sign Language (AdaSL) and Kata Kolok (KK) tend to have only the colors on the left side of the hierarchy, whereas larger urban sign languages such as Finnish Sign Language also have the terms on the right (such as brown for example). Furthermore, Adamorobe Sign Language has just one manual sign with three different Twi mouthings for the three basic colors "black," "white," and "red" (Nyst, 2007) as shown in Figure 1; Kata Kolok has separate signs for these and for yellow, as well as a single sign for "grue", a color term that includes both shades of green and shades of blue (De Vos, 2011). To express colors for which they have no lexical sign, both sign languages tend to use pointing to objects in the vicinity. This strategy has also been reported in Al-Sayyid Bedouin Sign Language in Israel and Ban Khor Sign Language in Thailand (De Vos, 2011). As the present study was mainly focused on the evolution of lexical forms, we reduced signers' options for adopting pointing as a strategy by controlling the lab environment.

In addition to summarizing patterns and constraints in color term development, Berlin and Kay's (1969) hierarchy is useful as a framework for predicting the relative iconic-indexical motivation of color terms (De Vos, 2011; Sagara and Zeshan, 2016; Palfreyman, 2019). One main reason for less iconicity on the right side of the basic color term hierarchy is that many sign languages tend to use fingerspelling or borrowing to create these signs. Conversely, color terms on the left side of the hierarchy

FIGURE 1
Signs for "white," "black," and "red" in Adamorobe Sign Language (reprinted with permission from Nyst, 2007, p. 93).

have been found to be more often motivated by visual iconic-indexicality in sign languages, relative to terms on the right side of the hierarchy. For example, cross-linguistically, many signs for "white" refer to the teeth; many signs for "black" refer to hair; and signs for "red" tend to refer to the lips. On the other end of the color term hierarchy we often see more arbitrary signs, such as the Indian sign for "green", which is produced with a 5-hand on the chest and those not have an apparent motivation.

Iconicity in color terms can also incorporate signs representing objects to indicate the color as a whole (similar to "olive" or "sage" in English). Examples of this in our dataset were references to the sun (the downwards + hand-opening representational movement), or to gold (the movement of placing a ring along the ring finger) to refer to "yellow". Another case in point is signing LEMON to mean "yellow", which incorporates enacting movement of squeezing a lemon or slicing it in half, the iconicity here used to refer to the peel. This sign is not used to refer to the lemon, but to indicate the color of the lemon, indicating an iconic-indexical correlation. At the same time, the terms on the right side, such as "pink", are more likely to show sociolectal variation within one and the same sign language compared to terms on the left (Sagara and Zeshan, 2016). Therefore, one might predict that Berlin and Kay's hierarchy would also emerge in a cross-signing context in terms of which types of iconic motivation are more prevalent on either side of the implicational hierarchy.

Biases in the cultural evolution of expressive forms

Tamariz et al. (2014) investigated the evolution of expressive forms within an experimental paradigm. The study used a game similar to Pictionary, where one participant draws a concept for the other player to guess. Four pairs of participants drew pictures for each other. Each drawing was assigned to a category based on the general strategy (a "variant"). For example, to communicate the concept "soap opera", one variant was to draw two people and a heart plus a television, while another variant was to draw a bar of soap and a singer. Participants played the game repeatedly while swapping partners, so that everybody played with everybody else for all concepts. This allowed individual variants to be transmitted across the population. For example, one participant who had observed the "bar of soap + singer" variant for "soap opera" chose to reproduce this. Since it was an effective strategy, it spread until everybody was using it in the final round. So "bar of soap + singer" was selected by a series of biased reproductions. Using this paradigm, Tamariz et al. found that variants were selected based on their intrinsic properties (content-bias), that is variants are more likely to be adopted because they are easy to understand, efficient to produce, or memorable.

The current study uses this cultural evolution paradigm within a cross-signing context, considering context biases, frequency biases, coordination biases and interaction biases. Starting with context biases, an obvious factor is the effort it takes to produce a sign, which can be measured by the length of time it takes to produce a sign. This is similar to spoken language, but other types of properties are worth discussing in some depth for sign in particular. As summarized in Figure 2, color signs can be understood in terms of categories based on the content of the sign. When using signs to represent colors, a first distinction is between signs that are arbitrary and those that are non-arbitrary or motivated.

Non-arbitrary color signs, that is, signs that are indexically or iconically motivated (Taub, 2001, p. 47; see also Section Iconic motivation below), may be easier to understand, so might be

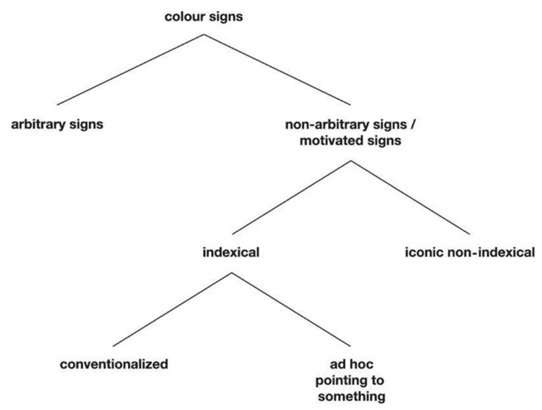

FIGURE 2
Content-biased categories to represent color words.

selected by a content bias. Non-arbitrary signs can be further subdivided into indexical signs and (non-indexical) iconic signs. In order to make this distinction, the term "indexical" is used in a specific way here which is different from its usual meaning in semiotics in the context of spoken language (cf. Parmentier, 1994). "Indexical" here refers to pointing with the index finger, so all color signs where the index finger points to or touches a referent associated with the intended color are called "indexical". While the meaning of an iconic sign arises from a relationship of resemblance. This includes, for instance, pointing to the teeth to express WHITE or touching the lips for RED. Unlike in the literature on semiotics, "indexical" in this sense makes reference to the physical form of the sign, that is, the index finger pointing.

Non-arbitrary signs of the indexical type may be conventionalized, such as pointing to the head in the sign BLACK (the color represented by the hair), or *ad hoc*, such as GREEN when represented by pointing to a green wall. Conventionalised signs are consistently articulated in a specific way, e.g., stroking the scalp twice with the index finger for BLACK in Indian Sign Language, and hence these are listable vocabulary items. By contrast, when a signer points to a green wall that happens to be in the vicinity, the indexical sign falls into the "*ad hoc*" type.

The second category of motivated signs is called "iconic non-indexical", and these typically refer to colors by representing an object that prominently exhibits the color in question. In this case, the intended color association is not physically present in a visible object to be pointed to. Instead, an iconically-motivated form is used to represent an object that has that color, based on the signer's experience and mental imagery of the object's color. So the form is iconically motivated by that color in an indirect way only. In our data, this category contains signs such as "flower" for PINK and "lemon" for YELLOW. For each color, there are of course a wide range of objects that could be used for this process; for instance, "yellow" might be indicated by iconically-motivated forms referring to the sun, a lemon, a gold ring, a reflective vest, or reflective lines or strips on the road. The internal logic of this content bias is different in that these associations may or may not be shared across signers initially. For instance, flowers come in many colors, other than pink. However, when a signer believes that pink is a common flower color and that this association is shared with the addressee, this may result in expressing the concept of smelling a flower as a way of referring to the color pink.

However, content biases may not fully explain the selection of expressive forms in cross-signing. For example, Whynot (2015) found that the iconic or indexical nature of signs did not generally aid naïve participants' comprehension of International Sign in a lab-like setting. A frequency bias is an obvious alternative: participants may be more likely to reproduce a variant if it has been observed frequently. Alternatively, coordination bias is the bias for an individual to adopt the behavior of others (Boyd and Richerson, 1988; Henrich and Boyd, 1998). In this experiment, participants can either try to adopt the signs that others invent (allocentric), or try to promote their own signs (egocentric).

In addition to the biases described above, we hypothesize that the selection of cross-signing variants may also be subject to an "interaction bias". This refers to the possibility of a person to select a sign or word that is highlighted within an interactional sequence. Specifically, we looked at the influence of whether or not a form was used within a particular type of sequence, such as repair, try-marking, or teaching. There are several hypotheses for how each of these contexts could affect the likelihood of a variant's reproduction. On the one hand, using a variant in an explicit teaching context or try-marking context (where a sign is proffered tentatively and quizzically, Sacks and Schegloff, 2007) may draw attention to the variant or reinforce the memory of the variant for the interlocutors. This would predict that the presence of these factors would cause an increase in the frequency of a given variant. However, these contexts are often employed when there is some kind of trouble in communication (e.g., the signers have different native signs for the concept or one interlocutor does not understand the sign). Therefore, if a variant appears in these contexts it could be an indication that it is not an effective variant (e.g., its meaning or referent is not transparent, or it causes confusion of some kind). In this case, one would predict that the presence of these factors would be an effect of poor suitability and predict a decrease in frequency. Cause and effect are often difficult to tell apart, but at least in this case they make different predictions about the direction of the correlation.

Methods

Participants

Each of the four participants in our study were fluent in the national sign language of their home countries (Jordan, Indonesia, India and Nepal) in addition to having some literacy skills in the written language(s) used there. Before flying to India to participate in this study, all signers had minimal past experience with international deaf contexts and met each other for the first time at our first recording time. The participants' language backgrounds are summarized by Table 1. The participants had very limited international experience and no experience with each other's sign languages. The participants could read and write but in different languages with a mixture of orthographic systems. While they had some exposure to written English, most were on the order of a few dozen words. Participants did use signs from their own sign languages, though this only accounted for 7% of variants used in the task. In any case, we are not trying to claim that the participants invented a new language from scratch, simply that they started with no established linguistic conventions between them. This study focuses on the selection of variants, rather than the innovation of variants.

TABLE 1 Language backgrounds of the cross-signing participants in our study.

Participants	Language background
Signer 1 **Family background:** Hearing parents **International experience:** No experience	**Fluent**: Jordanian Sign Language **Intermediate**: (written) Arabic **Minimal**: (written) English
Signer 2 **Family background:** Hearing parents **International experience:** No experience	**Fluent**: Indonesian Sign Language (BISINDO) **Intermediate**: (written) Bahasa Indonesia **Minimal**: (written) English
Signer 3 **Family background:** Deaf parents and siblings **International experience:** No experience	**Fluent**: Nepali Sign Language **Minimal**: (written) Nepali, (written) English
Signer 4 **Family background:** Hearing parents **International experience:** Some experience of meeting deaf people from other countries.	**Fluent**: Indian Sign Language **Intermediate:** (written) English **Minimal**: (written) Hindi

Procedure

The experiment took place in a minimally decorated room and the participants and coordinator wore black clothes. Participants were seated opposite each other at a table. A screen was placed between the participants, to one side, so that they could see each other directly, but there was an area of the table which was not visible to each participant. Participants engaged in a kind of spot-the-differences task in pairs. Almost identical cartoon picture was given to both participants in the pair (see Figure 3). On each picture, five items were colored. Of these five items, two were colored the same across both pictures, and three were in different colors (see Figure 4; the researcher explained that there were three differences). The participants could not see their partner's picture. The participants were told to communicate so that they discovered which items were colored differently and what those differences were. The small rectangles shown in the picture were necessary to signal to the participants that they should sign about that color. For example, the image on the right shows a white apron, which participants might have ignored if the rectangle was not there to indicate that it was a relevant item in the game.

FIGURE 3
Example of the spot-the-differences stimuli presented to each participant.

In order to indicate to the coordinator which colors they thought differed, each participant was given a picture (such as one of the images in Figure 3) and a set of 24 color chips (see Figure 4). When a participant discovered a similarity or a difference, they placed a color chip of the color of the other's stimulus in the relevant location on their own picture (their partner could not see this). When the participants were satisfied that they had discovered all the similarities and differences, they signaled this to the coordinating researcher, who recorded the placement of color chips on the images. At this point, participants could look at each other's pictures to check their accuracy, and ask questions if they wished. This was to verify that the participants had understood the color signs that they received. Throughout the experiment, there was no overt control over the participants' behavior; they negotiated the strategies and roles themselves (no participant was assigned as "director" or "matcher" by the coordinator), even when participants used unexpected strategies. This was done explicitly to promote a greater

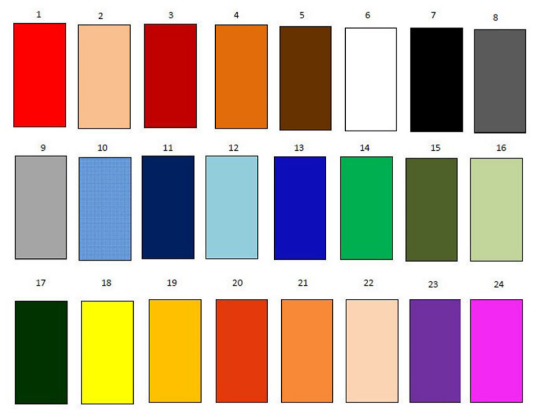

FIGURE 4
Color chips and their identifying numbers.

level of comfort for the participants and to elicit more natural utterances, including spontaneous try-marking and repair attempts.

A game consisted of completing three rounds, so that each pair saw three pictures, giving them the opportunity to sign about 24 colors (two identical colors + six differing colors in each pair of pictures). After each game, the participants swapped partners and played the same game with a different partner. This repeated until everybody had played with everybody else. Each picture was used more than once but the colors were switched so that participants did not receive the same color arrangement on the same picture twice.

This procedure was repeated three times: once during the first time that the participants met each other, once after 1 week of living together, and once after 3 weeks of living together. All games were captured using three video cameras giving a wide shot of both signers, and a frontal shot of each signer. This resulted in three video-recordings for each session, allowing for in-depth transcription of the cross-signing interactions that ensued.

In order to identify variants that originated from participants' native sign language, a post-doc interview was conducted by an assistant about what signs they used for various colors in their own sign language, and whether they knew of any variants in their own or other sign languages. These conversations were recorded so that they could be cross-checked with the experimental data during the analyses. That color from other languages, we would like them to tell us of all such variants. Moreover, the first author watched the data clips with the participants and their assistants to explicitly verify the origin of the signs they used.

Transcription and coding

The games during the first and third meetings were transcribed using ELAN (Crasborn and Sloetjes, 2008) for a corpus of 3 h and 38 min. Only color terms were transcribed. Each occurrence of a term was coded for a range of features:

- The target stimulus color the signer was meant to express. We use capitalized words (e.g., YELLOW) to indicate that these refer to the referent in the images or color chips. Since color category boundaries can differ between cultures, we don't make any claims about concepts.
- The color chip that the interlocutor selected.
- The origin of the sign, e.g., the participant's native sign language.
- Whether the sign was iconically motivated.
- Whether the sign was indexical, including whether it indexed the body or something else.
- Whether the sign appeared in a repair sequence, and whether it was in the trouble source (a turn "T-1" occasioning repair), or in the turn initiating repair ("T0" in the parlance of Dingemanse et al., 2015). In addition, variants were coded for whether they were a Candidate Understanding, i.e., a subclass of repair initiations that involve the offer of a sign with an equivalent meaning to the one articulated in the trouble source (cf. Dingemanse and Enfield, 2015).
- Whether the sign occurs in a "teaching" turn that explicitly instructs their conversational partner on how to use a particular sign, or the presence of any try-marker, such as a hold, mouthing, repetition, or decrease in signing speed (Moerman, 1988; Sacks and Schegloff, 2007; Byun et al., 2018).

Reliability

The third author annotated a random selection of 52 variant tokens (10%). Agreement was assessed using Cohen's Kappa. The agreement for different measures varied from "slight" to "fair" [Try Marking $\kappa = 0.3$ (0.01, 0.59); T0 $\kappa = 0.5$ (0.22, 0.77); T-1 $\kappa = 0.18$ (−0.11, 0.47); Teaching $\kappa = 0.47$ (0.16, 0.78); Candidate understanding $\kappa = 0.27$ (−0.24, 0.77)]. These values reflect low agreement. When the first coder and the coder conferred, they were able to reach a consensus, siding with the first coder. We suggest that the low values may therefore not reflect unreliable measures, but instead simply indicate that the coding task requires taking the context and interaction history between participants to be taken into account. Coding individual variants in isolation is therefore not a good way to assess reliability, but there are few other options given time constraints and required expertise in cross-signing. Given the fact that consensus was reached after contextualization and discussion of the items at hand, we proceed assuming that the coding is justifiable, and demonstrate that the variables above are sensibly related to our other measures.

Data processing

The transcription information was extracted automatically from the ELAN transcription using a custom python script and the *pympi* library (Lubbers and Torreira, 2014) and converted to a spreadsheet for further processing. Various other measures were calculated automatically based on these, including the length of time for the production of each sign and the trial length. Trial length was calculated by from the beginning of the first description of the target color, to the end of the final utterance prior to the interlocutors selecting the color chip. Accuracy was not analyzed because the signers were able to select the correct color in every case, an observation which speaks to the efficacy of cross-signing even in first encounters.

The experiment reported here was designed to challenge signers to differentiate between a range of 24 distinct colors, to make sure the task at hand was not too trivial at the final round. However, similarities in some of the variants rendered it unnecessary to analyze each color separately, particularly as some of the color chips represented a shade of one hue. Whilst many of these shades have individual color terms in English, such as jade, olive and sage for the aforementioned shades of green, respectively, in our data such subtle differences were communicated by non-manual modification of the sign GREEN, rather than a different lexical variant. The merging of shades resulted in a reduction from the initial set of 24 colors by combining related shades as follows (the numbers in brackets refer to the color chip numbers in Figure 4): WHITE (6), BLACK (7), RED (1, 3, and 20), GREEN (14, 15, and 16), PINK (4, 11), BLUE (10, 13), GRAY (8, 9). Variants for PURPLE was omitted from the final analysis due to the repeated difficulties experienced by the participants in attempting to express this color and the amount of retries that were unsuccessful which could have skewed the data. There was only one variant used for WHITE throughout the data set, i.e., an indexical point to the teeth, and this was removed for lack of initial variability. The final analysis focuses on seven colors: BLACK, RED, GREEN and PINK, BROWN (5) and YELLOW (18), exemplified a total of 491 times.

Statistical analysis

In order to assess the strength of each bias on the variants that were selected, we conducted a statistical analysis of the data. Data was aggregated for each variant used to refer to each of the seven main colors. Here we use a regression model that predicts the frequency of a variant in the final week according to various properties of the item and how it was used in interaction. The results indicate which properties are important for the selection of variants in this experiment, helping us understand the process of cultural evolution.

A mixed effects analysis framework (lme4, Bates et al., 2015) in R (R Core Team, 2016) was used to predict the frequency of each variant in the final week from variables in the first week, with a random effect for each target color. A Poisson distribution was used to model the frequency data directly. It is possible that an indexical strategy, particularly body-indexical signs, would be more effective for some colors than others, and so a random slope for the indexicality of the variant by target color was added. The significance of fixed effects was obtained from model comparison tests (see Table 2 for statistics). These were used to identify a final model for analysis using forward selection of variables. See the supporting information for full details at https://github.com/seannyD/ColourInteractionExperiment.

Results

The final dataset included 491 sign instances consisting of 75 unique variants. Some variants were used when referring to multiple target colors, giving 97 unique combinations of variants and target colors. Figure 5 (left) shows the average trial length reduces from the first week to the second week: participants are improving their communicative efficiency (mean in week 1 = 18 s, mean in week 2 = 3 s, $t = 4.06$, $p < 0.001$). Figure 5 also shows (right) the average sign length (the time taken to produce a single variant). A pressure for production efficiency (a type of content bias) might predict that signs would become shorter. Indeed, overall the sign length decreases (mean in week 1 = 1,707 ms, mean in week 2 = 1,190 ms, $t = 4.13$, $p < 0.001$). However, the results show that the average signal length does not decrease for every color, and even the average decrease is not enough to explain the decrease in trial length. This suggests that the interactive negotiation of meaning is becoming more efficient, rather than the signs themselves. This could be due to converging on conventional variants, reducing the number of turns or reducing the number of repair sequences. This may be indicative of a rapid initial evolution in the cross-signers' selection of variants.

The final statistical model included the following fixed effects (all based on data from the first encounter): the indexicality of the variant (not indexical, indexical of the body or indexical of something else); whether the variant had been explicitly taught at any point; whether the variant had appeared as a try-marked sign; whether the variant had appeared in a repair trouble source (T-1); whether the variant had appeared in any type of repair initiation (T0, candidate understandings and checks were collapsed); the identity of the first signer to use the variant; the total frequency of the variant across all color contexts; and the average length of the variant in milliseconds. The model comparison tests also suggested that there was a significant interaction between frequency and each of three interactive

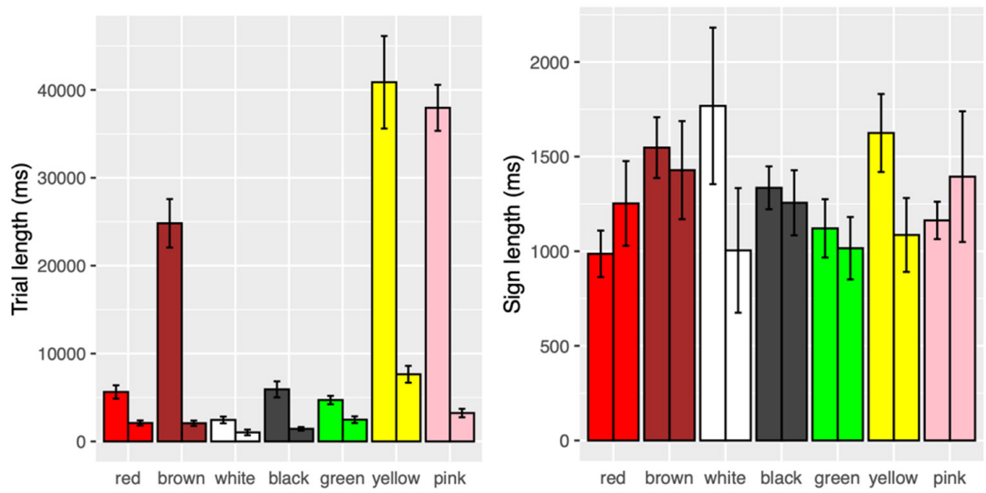

FIGURE 5
Trial length and sign length for different target colors. **(Left)** Average length of trials (start of first turn to the participants noting a color difference on their sheet) for the first week (left bars) and the final week (right bars). **(Right)** Average length of individual sign variants for the first week (left bars) and the final week (right bars). Error bars (black lines) indicate the standard error.

variables: use in repair initiation, teaching, and try-marking. The final model fits the data reasonably well: when using the model to predict which variants survive to the final week and which do not, it predicts 93 out of 97 correctly.

Figure 6 below shows the model predictions of how these features relate to the probability of a variant surviving (see Table 2 for statistics). There are indications of a content bias: variants were more likely to be used in the final week if they were shorter to produce (a content bias). Also, although there was no significant main effect of indexicality, the effect of indexicality differs significantly between the target colors (significant random slope for indexicality by target color, $\chi^2 = 79.3$, Df $= 6$, $p < 0.001$). The effect of indexicality is larger for black and red and smaller for pink and green.

There is also clear evidence of a frequency bias: variants were significantly more likely to be reproduced in the final week if their frequency was higher in the first week.

There were also significant effects of the interactive context: Variants used in trouble source turns were less likely to survive, whilst those used in T0 (repair-initiating) turns, teaching, and try-marking were all more likely to survive. There was also a significant main effect of the first user: all other effects being equal, signs first used by the signers from Jordan and Nepal were more frequent in the final week.

Model comparison also revealed three significant statistical interactions: between T0 and frequency; between teaching and frequency; and between try marking and frequency. To understand the statistical interactions, it's useful to visualize the relationship between frequency in the first week and frequency in the second week for each type of context (Figure 7). Here we can observe several patterns. When a variant is infrequent, there is little difference between whether it appears in a teaching context or not. However, a frequent variant gets a "boost" if it also appeared in a teaching context. The same is true of variants that appear in T0 and Try Marked contexts.

Discussion

In this section, we discuss the evidence in the results for each type of transmission bias (frequency bias, content bias, and coordination bias). For each type of bias, we argue that the effects are bound up with the moment-to-moment interactive context.

Frequency bias

As expected, variants that were more frequent in the first week remain more frequent in the second week, demonstrating a frequency bias. We also found significant interaction effects that suggest a relationship between the frequency bias and the interaction bias. The effects of a variant appearing in a teaching turn, or T0 turn or being try-marked are stronger if the variant has a higher frequency in the first week. This might suggest that the effects are additive. However, for low-frequency variants, the probability of selection is actually lower if they appear in teaching or try marked sequences. This might suggest that these interactional contexts are polarizing. They indicate some uncertainty about the effectiveness of the variant. If the recipient understands, then it might be taken as an opportunity to cement a convention. If they do not understand, then the producer might avoid that variant in the future. This

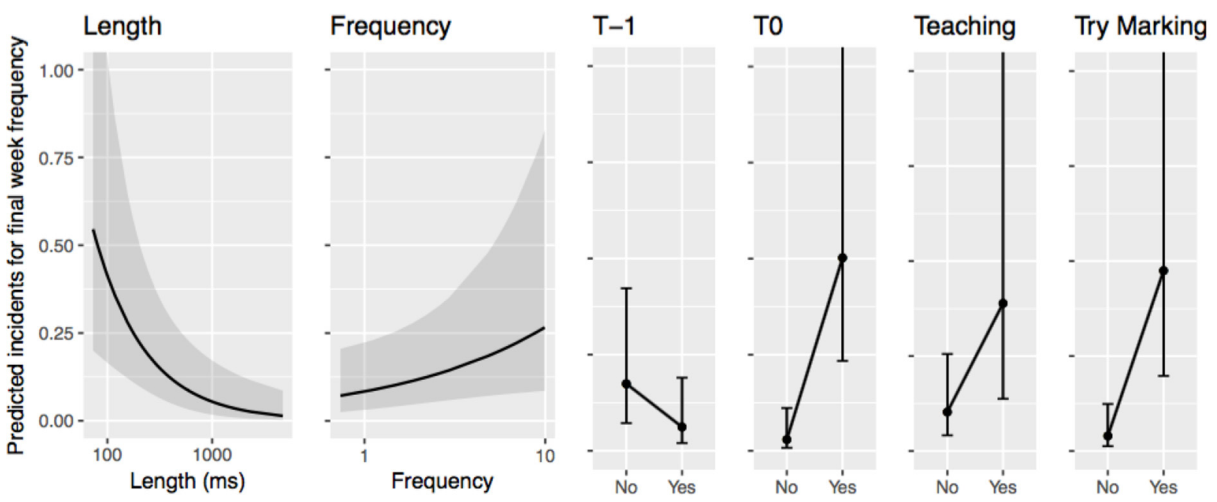

FIGURE 6
Predicted incidents for final week frequency from the model for significant main effects. From left to right: length, frequency, T-1, T0, teaching, and try-marking. In the final four columns, the predictions are shown according to whether the variant did ("Yes") or did not ("No") appear in the particular context suggested by the heading. For example, variants used in try-marking situations had a higher final frequency than those that did not appear in try-marking situations. Points higher on the vertical axis in this figure indicate a higher likelihood of surviving to the final week. For length and frequency, the black line represents the model's predictions: The probability of a variant surviving into the final week is higher for short, frequent variants. The gray ribbon represents the model's uncertainty. For the last four plots, black dots represent the model's predictions of the mean probability for each category of variant. The whiskers represent the uncertainty of the predictions. For four different interactional contexts, the prediction of the final week frequency is shown according to whether the variant is used ("Yes") or not used ("No") in that context.

TABLE 2 Results of the model comparison tests for different variables.

Variable	Beta	Log likelihood difference	χ^2	DF	*P*
Week 1 frequency	7.2	−29.12	58.24	1	<0.001*
Length	−1.1	−2.47	4.95	1	0.03*
Indexicality	Indexical signs = −1.8, body-indexical = 0.85	−2.11	4.21	2	0.12
Teach	11	−6.59	13.17	1	<0.001*
Try-marking	1.3	−2.71	5.43	1	0.02*
T0	10	−10.89	21.78	1	<0.001*
T-1	−2.3	−2.31	4.62	1	0.03*
Identity of first user		−4.4	8.81	3	0.03*
T0 × Frequency		−10.9	21.79	1	<0.001*
T-1 × Frequency		−9.06	18.13	1	<0.001*
Try-marking × Frequency		−11.19	22.37	1	<0.001*

The columns show the following information. Variable: name of the variable. Beta: the estimate of the variable value in the model. This is the increase in frequency for each unit of increase in the given variable. Often these are hard to interpret directly, but at least give an indication of the direction of the relationship (positive or negative). Log likelihood difference: improvement in how well the model fits the data when including this particular variable. χ^2: indication of the relative strength of the improvement. DF: extra degrees of freedom in the model when adding the variable. *P*: *P*-value which indicates the probability of seeing this amount of improvement due to chance, taking into account the number of extra degrees of freedom. A low value suggests that the null hypothesis that the variable has no effect and can be rejected. *Significant at $P < 0.05$.

suggests a relationship between cognitive factors and usage, also highlighted in work on language change (Bybee, 2010). These tentative explanations would need to be explored in a larger sample or a dedicated experiment, but the main point here is that there are potential relationships between established transmission biases such as frequency and interactional contexts or metalinguistic aspects that are worth exploring in the future.

Also in relation to frequency, we considered Zipf's (1935) observation that more frequent words become stronger over time in order to facilitate efficient communication. Zipf's general point is that communication systems should evolve

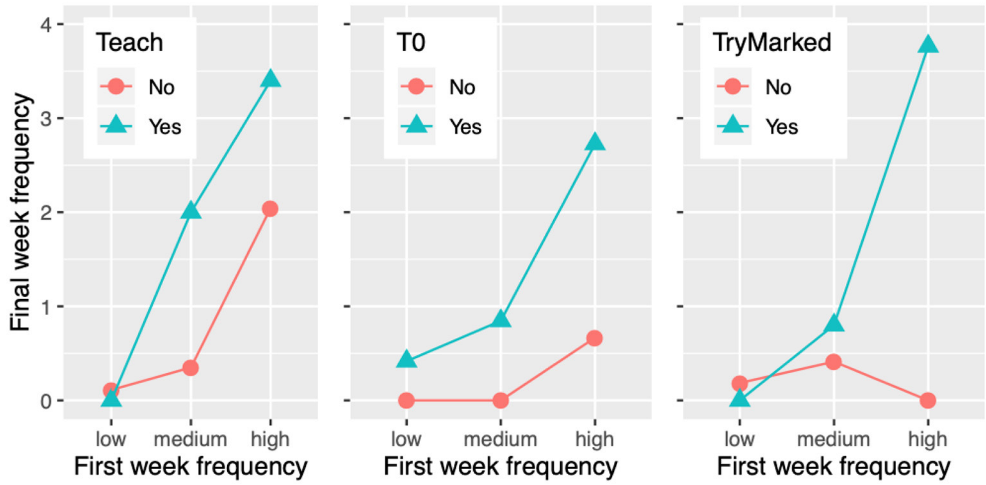

FIGURE 7
Relationships between frequency and interactional effects for teaching **(left)**, T0 **(middle)** and Try-marking **(right)**. The vertical axis shows the frequency in the final week. The horizontal axis shows the frequency in the first week, cut into three bins by tertile (1–2, 3–6, 7+). Points on the graph show mean frequency for a given interactional type and first week frequency bin. Since the purpose is to illustrate the direction of interaction effects, the uncertainty is not shown.

to allow efficient communication. We observed that more frequent variants tended to be shorter ($r = 0.1$, $p = 0.03$), though the association is similar even in the first week ($r = -0.08$, $p = 0.07$), so we cannot claim that this feature evolves through interaction.

Content bias

Indexicality

In this section, we present a qualitative analysis of how indexicality featured in our data to highlight the theoretical contributions cross-signing makes to this phenomenon.

There was no overall effect of indexicality on the selection of variants. The probability of a sign surviving was roughly equal whether it was not indexical (5.1%), indexical (4%) or indexical of the body (4.1%). However, the effect of indexicality was significantly different for different colors. The effect is strongest for Red and Brown (Figure 8). For example, the mean final week frequency for variants referring to Red and Brown are lowest for non-indexical variants (all have zero frequency in the final week), higher for non-body indexical variants (mean = 0.7 occurrences, sd = 1.5), and highest for variants that index the body (mean = 2.4 occurrences, sd = 4.5). This aligns with the observation that an indexical strategy depends on the environment: if there are no pink or green things to point to, then those color expressions will not be employed. As noted in the qualitative discussion of indexicality in the following section, body-indexicality is important for the signs BLACK and WHITE, but there were relatively few variants for these signs so the effects of indexicality are uncertain.

Indexicality takes four forms in the present data: pointing to something on the body; demonstrative pointing to objects in the immediate surroundings, such as a tree visible from the window; pronominal pointing to an entity that is not physically present; and other uses such as pointing to a sign or handshape. The first function is seen in the variants BLACK (which involves pointing to the hair), RED (mouth), WHITE (teeth), BROWN (skin), and PINK (tongue). The interviews revealed that indexical variants to point to the skin to mean BROWN included the Jordanian signer pointing to the arm, the Indonesian signer pointing to the back of the hand, and the Indian and Nepali signers pointing to the face.

While indexicality is clearly a useful strategy, even indexical signs may require contextual interpretation and negotiation of meaning, which means that indexicality may not always be the best option. For example, the data show that the cross-signers rapidly converged on a sign for BLACK that touches hair on the head. This variant was familiar to all of the signers except the one from Jordan. At first, the Jordanian signer tries two lexical signs from his language for BLACK, including brushing the fingers against the cheek, representing a beard (see Figure 9). Of course, the sign might be considered indexical for the Jordanian signer, because he had facial hair. However, this affordance was apparently not noticed by the other participants. Consequently, the Jordanian signer stopped using it in favor of the one referring to hair on the head, which had a common referent for all participants. Similarly, for RED, the Indian signer used an indexical point to the forehead where a red Bindi dot typically

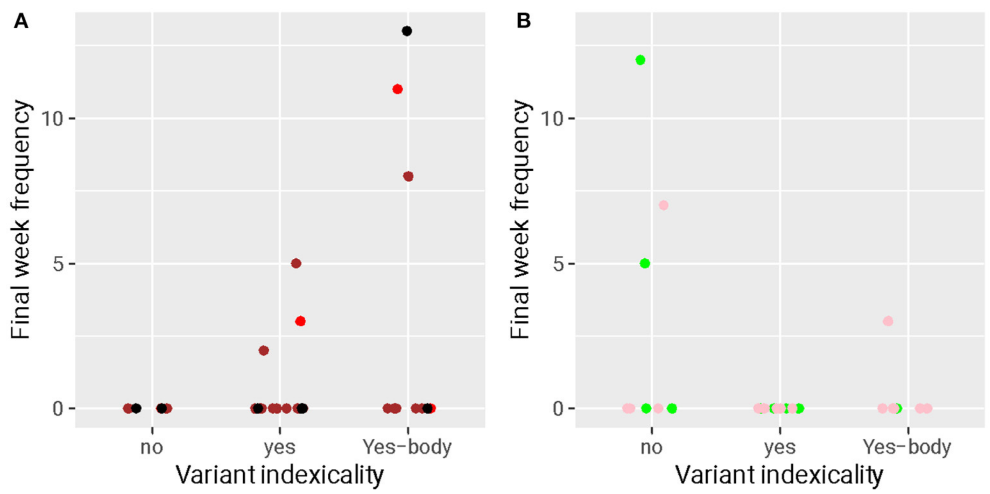

FIGURE 8
Frequency in the final week as a function of indexicality of variants, for various colors. The effect of indexicality was stronger for red, brown and black **(A)**, and weaker for green and pink **(B)**.

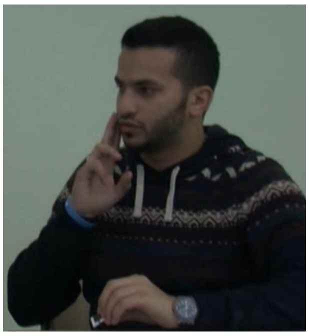

FIGURE 9
Sign from Jordanian Sign Language that means BLACK, and makes use of visual indexical motivation referring to a beard.

appears. This is culturally contextual, and was abandoned in favor of pointing to the mouth instead.

In summary, while indexical signs seem like effective variants that will be replicated, their fitness still depends on establishing common ground and negotiating the context of their reference. This negotiation depends on interactive conversation, showing how transmission biases and interaction are linked (see for example Zeshan, 2015; Bradford et al.'s, 2020).

Interestingly, the data contains several cases of pointing to a handshape or sign, for example when making it clear which sign is being targeted for repair or teaching. This phenomenon is not covered in the existing literature to our knowledge, and represents an interesting exception to the rule that deictic reference is either exophoric or anaphoric. Because the phenomenon involves a visible item or location in the immediate setting, it is exophoric; however, because it involves a reference to previous discourse, it is also anaphoric; yet, because it has features that contraindicate both categories, it may fall into neither. We coin the term *esophoric* here, deriving from the Greek stem -eso "within", to denote this phenomenon. A remaining question is whether this phenomenon is not just restricted to the visual-gestural modality but also specific to signing, or whether an equivalent could be found in the multi-modal utterances of speakers as well.

Iconic motivation

Some telling examples of iconically motivated forms in the data set include signing CLOWN by referring to the round RED nose, and tracing a circle on the cheeks for PINK, or portraying the actions of slicing and squeezing a lemon for YELLOW. The forms used for the iconicity strategy might include classifiers and enacting (e.g., "tasting" a sour lemon), and it may involve representing the entire signified item or only part of it. Dingemanse (2015) notes that iconicity is a concept of wide extension and consequently difficult to code. For example, "yellow" might be described on in a single turn as LEMON-SHAPE, SLICE-LEMON, TASTE-LEMON, a remaining question is whether different subtypes of iconic motivation, related to, e.g., tasting vs. handling a lemon may affect its selective fitness (as a form of content bias). A related point is that making the connection between a referent and color can be dependant on the cultures involved. For instance, one signer might use signs referring to reflective road strips or vests to mean "yellow", but if the other signer comes from a culture where these are not used or where they have a different color or appearance, the meaning will not be understood.

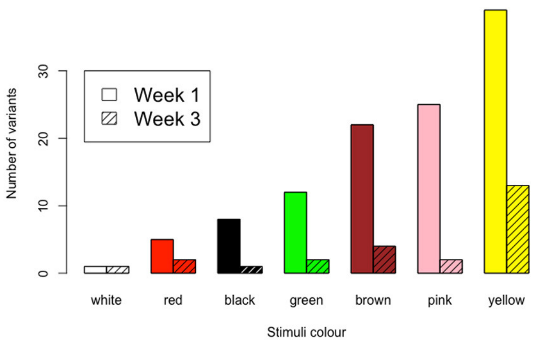

FIGURE 10
Number of variants used in the first week (left column of each pair) and the final week (right column of each pair, shaded).

Another challenge is that there is a difference between a sign articulated by pointing to something visible in the room (e.g., the signer's skin) and a visually-motivated iconic sign referring to, for example, a flower. This is because the color of the visible object is clear to see in the immediate setting (a case of indexical iconicity according to Figure 2), whereas the color of the object referred to by the iconic sign is not, and signers may differ in how they interpret what color is intended as the referent due to the fact that they have to rely on their mental association of the object with a certain color. For example, flowers can be many different colors, so the sign FLOWER (an instance of non-indexical iconicity as per Figure 2) will not necessarily make a signer think of "pink" on its first use. Our data show however, that such conventions can be achieved interactionally over relatively brief periods of time, at least in an experimental setting where there is communicative pressure to differentiate color expressions.

Non-indexical iconicity is more common for colors for which body-part indexicality is less feasible. For such colors, there can be many different iconic variants; e.g., for "yellow" the possibilities include referring to the sun, a lemon, car headlights, a reflective vest, and strips on the road. For "green", there are also many different variants initially, but most of these refer to trees or leaves, so they are in the same general category, making it easier to narrow down, select and agree on a common variant. For "yellow", this is more difficult, because the concepts may be very varied, so it took longer for the participants to narrow down the variants and in fact they were still dealing with a large number of variants in the final week (see Figure 10).

Figure 10 shows that there were large numbers of variants used in the first week for both the concepts of "pink" and "yellow", but by the last week these had both been reduced considerably, especially the number of variants for "pink". There remained a relatively high number of variants for "yellow" in the final week, compared to the other colors. In the sections that follow, a situated understanding is provided as to why this was the case in our data set.

Moreover, these two color concepts ("pink" and "yellow") also prompted multi-sign sequences that combined several strategies. For instance, in the first round, the Indian signer made a sign based on the action of squeezing and tasting a lemon. Then he fingerspelled L-E-M-O-N using the International handalphabet, and then he signed SUN. He produced a range of variants, but they were not understood by his interlocutor, the Jordanian signer. When signing "pink", the Indian participant articulated the sequence TONGUE RED DIFFERENT.

In particular, many variants could be used to represent the color "yellow", e.g., articulating LEMON or GOLDEN-RING. SUN was used to represent red, yellow, orange or gold, because of the sun's variety of colors and the way these are perceived in different cultures. Similarly, there are cultural differences in the colors of vests in uniforms worn by, e.g., police officers, which can vary from country to country. These may be, e.g., orange, fluorescent green, black or pale yellow. Therefore, one participant might sign VEST POLICE to mean "yellow", but this may not make sense to another participant who comes from a country whose police officers wear black vests rather than reflective yellow vests. It seems that the wide range of variants for "yellow" is not a matter of interaction bias but of the diversity of color expressions and cultural differences causing a problem related to content bias which necessitates an extended interaction.

As noted above in Section Color terms in signed languages, Berlin and Kay (1969) claimed that there is an evolutionary sequence of colors in the world's languages. Colors tend to develop in stages as follows: (Black, White), Red, (Green, Yellow), Blue, Brown, (Purple, Pink, Orange). Berlin and Kay suggested this was due to functional pressures from an increasing need to express distinctions in more complex and technological societies. We note that the number of variants for each color in the first week has a similar order. We predicted that the first basic color words emerge because they are easy to point to on the body (cf. De Vos, 2012). Indeed, it was found that the number of variants in the first week is correlated with the proportion of indexical variants. For example, "white" is easy to point to (teeth), and so everyone quickly agrees on that variant, and "black" is also readily available, as none of the participants come from a culture where there is a lot of non-black hair in the population. "Pink" is harder to point to, so there is a wider range of strategies and less agreement. The only deviation is for "yellow". Therefore, it is suggested that the order of the evolution of color terms may be influenced by indexical motivations in interactive conversation not only in sign, but also in spoken languages. The idea is this: Colors are abstract properties that can most easily be referenced by pointing to salient co-present objects in the world; these pointings will initially serve as indexically motivated signs, as they are easier to "ground" and will have fewer competing variants—as we have seen with "yellow" lack of salience and too many possible competing referents hinders conventionalization. The fact that we mostly carry around with our bodies good and salient exemplars of black, white and red may account for the Berlin and Kay generalization these are the first terms to emerge evolutionarily. For other terms, like "blue" or "yellow", there may be many competing exemplars while none of them may be saliently or reliably co-present. In contrast, teeth, lips and hair are always available, and so might conventionalize faster (cf. Dingemanse, 2009; De Vos, 2011).

TABLE 3 Variants for "pink" produced by each participant during week 1.

	Team 1	Team 2
week1, round 1	India : [TONGUE + RED + DIFFERENT] Jordan : [FLOWER]	Nepal :[RED + BRIGHT + UNDERSTAND?] Indonesia : [BRIGHT?]
week1, round 2	India : [RED + TONGUE + FLOWER] NEPAL: [RED + DARK] India : [RED + BRIGHT]	Indonesia : [CLOWN + RED + BRIGHT] Jordan: [FLOWER]
week1, round 3	Nepal : [FLOWER] Jordan : [FLOWER]	Indonesia : [FLOWER] India : [FLOWER]

Interaction bias

Coordination bias

Coordination bias relates to the extent to which individuals adopt variants produced by others (allocentric bias) compared to using their own variants (egocentric bias, see Tamariz et al., 2014). According to the model, signs invented by the signers from Jordan and Nepal were more frequent in the final week ($p = 0.03$). However, the effect size is very small. We also looked at the relationship between the number of signs someone invents and the number they adopt, the Jordanian signer adopted more than he invented, while the other three signers invented more than they adopted. This might suggest that the Jordanian signer was more receptive and had less of an egocentric bias than the other three signers. While this pattern may not be reliable in the quantitative data, a qualitative analysis of the role of individuals shows some further effects of coordination.

For example, Table 3 shows the signs used for PINK in week 1. The Jordanian participant offers the same variant, FLOWER, for "pink" in rounds 1 and 2, during which the other participants used a mixture of variants, although it is not clear why FLOWER is selected to represent "pink" as opposed to representing any other color that is common amongst flowers, such as "red" or "white" or "yellow". In round 1, this offer followed a longer explanation by the Indian participant, who adopted the fewest variants from other interlocutors. This happened again in round 2 of the experiment (not further analyzed here), when the Indonesian participant signed CLOWN and RED+BRIGHT and the Jordanian participant responded by offering the FLOWER variant. By round 3, this variant had been adopted by both pairs. It is possible to conclude that the Jordanian participant's flexible communicative skills and the ease with which he offered this variant made an impression on his interlocutors which led to both teams selecting this variant. Also, the Nepali participant is skilled at overtly managing the communication, and initiates repair with RED+DARK in round 2. The Nepalese participant understood TONGUE+FLOWER from the contextual background, and confirmed the notion of "a light shade of red" by initiating a repair sequence using RED+DARK "dark red?", to which the Indian answered RED+BRIGHT "light red". Thus, in round 3, FLOWER was chosen rather than TONGUE, even though both of these were expressed by the Indian participant in the second round, because FLOWER is more abstract and does not involve the extra explanation of the difference between the intended color referent and the shade of the actual tongue being pointed to in real time.

The signing from the Indian participant reflected the egocentric bias, for example when he used a non-iconic sign for "green" (a flat hand on the chest) without any pointing, explaining, or iconically-motivated support. His interlocutor, the Jordanian participant, did not understand it and attempted to resolve the trouble by repeating the sign he didn't understand, and then making an iconic sign for "tree" and pointing to the green-colored wall to guess at the intended meaning. In contrast, when the Nepali participant was signing with the Indonesian participant, the former articulated her own variant for "green" and then signed TREE in a visually iconic way with one hand and pointed to it with the other hand. During the next round, the Indian and Nepali participants were paired together, and the latter referred to "green" by pointing to the wall. The Indian participant then seemed to make a candidate understanding by using his own non-iconic sign again. So, it is likely that he understood the meaning of the pointing, and this articulation of his own sign was not so much a query as an attempt to teach or influence his interlocutor. The adoption of several of the Indian signers' variants by the other participants could perhaps be due to the immersion of all of the signers in an environment where Indian Sign Language was the main visual language. This observation is consistent with Bradford et al.'s (2020) study on the development of the lexicon, where the same pattern of "home advantage" was found. As mentioned above however, our quantitative analyses do not reveal a statistically significant pattern for the overall data set.

"Explicit teaching" does not necessarily mean that the signer gives an explicit meta-indication that s/he is going to instruct the interlocutor on how to use the sign. Rather, it normally involves first establishing the general concept being communicated (e.g., through explaining or pointing to an object in the room), so that both interlocutors can confirm understanding, and then showing the sign for it in an explicit way, e.g., "Yes, as for (that concept), here is the sign for it, right here". This often involves pointing at the sign with the other hand, i.e., esophoric pointing. Another situation in which explicit teaching might arise is if the interlocutor signals trouble and asks what a particular sign means. After the explicit teaching, the signer may decide to ask "what's your sign for this (concept)?" The other signer will usually just sign it, and will not tend to preface it with "my sign for this concept is..." However, this is still regarded as explicit teaching in the data. In ELAN, it was necessary to code these distinctly as two instances of explicit teaching instead of one, even though they occurred in a single sequence and the second instance especially is not prefaced or accompanied by any structure drawing explicit attention to this being a teaching or demonstration. Such cases were coded and counted as explicit teaching for the data analysis because of the way they were acknowledged by the interlocutor.

Conclusion

This study conducted an experiment in a cross-signing situation. Participants had never met and had no knowledge of each other's languages. They had to complete a matching task in the domain of color. The participants then lived with each other for 3 weeks before repeating the task. This allowed us to combine the ecological validity of a cross-signing context, the control of experimental semiotics, and the longitudinal perspective by which selection of variants could be measured. We observed that, even when participants did not share linguistic or cultural backgrounds, the process of grounding is complex and requires active and intricate management of interaction. For success in their cooperative task, signers need to pay attention to each other, and pay attention to the message being articulated to succeed in understanding each other. Signers react to the cumulative success by continuing to add to the communication. This demands meta-attention not only to one's own choice of expression, but also the granting of a cooperative window that allows for the signaling of comprehension or the negotiation of meaning. According to Clark (1996, p. 241) "grounding hypothesis", the meta-communicative track or layer of communication is essential for establishing common ground. In the context of having to establish conventions, cross-signers need to work hard together to reach a mutual belief that they are sufficiently well understood.

This setting allowed us to examine the relative importance of various factors in the early stages of the evolution of a common communicative system. Models of cultural selection suggest that various biases influence the selection of variants (Boyd and Richerson, 1985). Although the results of this study exhibited effects of frequency, content, and coordination biases, there were also effects of the interactive context. Indeed, the measures of sequential context were stronger predictors than frequency or iconicity in this study. This suggests that selection is not just affected by what is produced, but *when* it is produced. These effects are, in principle, independent. For example, a variant might have a high frequency simply because it was poorly motivated and needed to be repeated several times in a repair sequence. In contrast, an easily understood variant may only need to be used once before the pair can move on. Given the results of our experiment we argue that, in order to understand the selection of variants, an understanding of the relationships between these different kinds of bias is required.

How should we conceptualize these relationships? In the broad models of genetic evolution proposed by Dawkins (1982) and Hull (2001), the gene is a replicator and an organism is a vehicle that interacts with the environment to cause the replicator to replicate. Croft's model of language evolution argues that this model also applies to language: the word/sign or phrase is a replicator and the individual language user is the vehicle (see Croft, 2000). In our study, the different signs are replicators, and the signers are vehicles. However, we find that the type of sequence in which a form is used matters more than the simple frequency of a form. Hull notes that in biology there are many levels of vehicle: cells are vehicles for genes, and organisms are vehicles for cells. Therefore, we suggest that there are two levels of vehicle in cross-signing and in conversation in general. The first is the language user, and the second, intermediary vehicle is the conversational sequence. The type of interactive sequence promotes (or inhibits) the replication of the signs within it just as a particular type of cell supports the replication of the genes within it. This is because on top of and beyond frequency, its form and motivation, or who uses it, the reproduction of linguistic forms is affected by the selective attention and subsequent learning that takes place within interaction. For cross-signing, this implies that the details of interaction are important for effective communication. In particular, the emergence of effective signs may be promoted by providing opportunities for the right kind of interactive sequences, for example explicitly encouraging interlocutors to use teaching, try-marking and repair. Furthermore, while cross-signing may be the context in which the role of the conversational sequence as a vehicle is most apparent, this double layer of vehicles may apply more generally to any case of the cultural transmission of language. It certainly fits with findings that demonstrate the importance of the history of interaction between interlocutors on the emergence of conventions (e.g., Motamedi et al., 2019), or the importance of repair in language acquisition (e.g., Clark, 2020), or with Enfield's notion of different "frames" of language (Enfield, 2014).

There are of course distinct limitations to this study, which examined the evolving repertoires of a small number of signers. It is possible that the results would be different when interacting in groups rather than pairs, or with a different sample of signers. There might be stronger coordination biases depending, for example, on the mix and balance of different cultures in a group. As noted above, the coordination bias was somewhat influential in the data because the Jordanian and Nepali signers were skilled in accommodating to their interlocutors' choices, while the Indian participant's signing suggested that the egocentric bias was at play (cf. Zeshan, 2019). Collecting data on cross-signing in groups would also more closely approximate the evolution of International Sign (IS), which has developed gradually across years of international gatherings such as events held by the World Federation of the Deaf (Hiddinga and Crasborn, 2011). The variants that appear in IS have been selected by participants at these gatherings. Its evolution has been continually driven by the input from new individuals, because the events do not involve the same people each time. There is a tendency for such individuals to conform to the majority, i.e., to the variants that are already in use, but this is not a certainty, and they may also introduce their own variants rather than following the majority in every instance (Efferson et al., 2008).

It is also possible that the domain of color is unusual in being about abstract properties that are often not inherent in any object (e.g., a shirt can be red, blue or green). But the results do suggest an intriguing possibility that an additional factor in the evolution of the Berlin-Kay color hierarchy is the relative ease of grounding the color concepts in interactive situations. The colors white, black and red, oftentimes being linked to body parts across signed languages (Dingemanse, 2009; De Vos, 2011), and in any modality the cultural evolution of variants for these colors may be affected by this affordance. Future fieldwork and lab experiments could help tease apart the contribution of grounding and other saliency properties.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material and data and code can be accessed at https://github.com/seannyD/ColourInteractionExperiment. Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval for this research was granted by the University of Central Lancashire's Ethics Committee as part of the MULTISIGN project. Informed consent through written and sign language modes was obtained from participants for taking part in the study and for the publication of any identifiable images or data included in this article.

Author contributions

SL, UZ, and CV have secured research funding for this project to be carried out. K-SB, SR, and CV conceived of the design of the study. UZ and CV organized access to the field site and supervised the fieldwork carried out by K-SB. K-SB transcribed and analyzed the data. SR and K-SB carried out the statistical analyses. K-SB, SR, SL, and CV wrote up the initial version of this article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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