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Segmentation of British Sign Language (BSL): Mind the gap!

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This study asks how users of British Sign Language (BSL) recognize individual signs in connected sign sequences. We examined whether this is achieved through modality-specific or modality-general segmentation procedures. A modality-specific feature of signed languages is that, during continuous signing, there are salient transitions between sign locations. We used the sign-spotting task to ask if and how BSL signers use these transitions in segmentation. A total of 96 real BSL signs were preceded by nonsense signs which were produced in either the target location or another location (with a small or large transition). Half of the transitions were within the same major body area (e.g., head) and half were across body areas (e.g., chest to hand). Deaf adult BSL users (a group of natives and early learners, and a group of late learners) spotted target signs best when there was a minimal transition and worst when there was a large transition. When location changes were present, both groups performed better when transitions were to a different body area than when they were within the same area. These findings suggest that transitions do not provide explicit sign-boundary cues in a modality-specific fashion. Instead, we argue that smaller transitions help recognition in a modality-general way by limiting lexical search to signs within location neighbourhoods, and that transitions across body areas also aid segmentation in a modality-general way, by providing a phonotactic cue to a sign boundary. We propose that sign segmentation is based on modality-general procedures which are core language-processing mechanisms.

Keywords: British Sign Language (BSL); Lexical segmentation; Language-processing universals.

Signed language produced by Deaf people in everyday conversation consists of a quasi-continuous stream of overlapping hand and facial movements. Comprehenders of signed language have to segment such input streams in order to be able to recognize individual signs, and hence understand other signers' messages. How then is signed language segmented? We attempt to answer this

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question here by comparing sign segmentation with what is known about speech segmentation. Speech also consists of a quasi-continuous stream of articulatory movements, so it too needs to be segmented. It is possible that, in spite of the substantial physical differences between spoken and signed language, there are general segmentation principles which can be used across input modalities. Alternatively, sign segmentation may be based, at least in part, on principles which reflect the specific characteristics of signed language. We ask here what the balance is between modality-general and modality-specific principles in the segmentation of British Sign Language (BSL).

The structure of BSL signs

Sign linguists agree that, across a range of signed languages, signs are decomposed into a set of minimal phonological parameters. For example, a wide set of studies have established that BSL signers use these phonological parameters during sign comprehension (Corina & Knapp, 2006; Dye & Shih, 2006; Orfanidou, Adam, McQueen, & Morgan, 2009; Orfanidou et al., 2010; Thompson, Emmorey, & Gollan, 2005). The basic phonological structure of a BSL sign, as in other signed languages such as American Sign Language (ASL; Stokoe, 1960; Stokoe, Casterline, & Croneberg, 1965), consists of four parameters (Cormier, Schembri, & Tyrone, 2008; Sutton-Spence & Woll, 1999; Thompson, Vinson, & Vigliocco, 2010): (a) location, or where the signing hand is located in relation to the body; (b) movement, or how the signing hand moves in space (e.g., in a circle or an arc, with wiggling fingers); (c) handshape, the form of the hand itself (e.g., fist, index, circular); and (d) orientation. We are concerned in the current investigation only with the first three parameters. Signs can share one or more of these parameters. For example, the BSL signs NAME and AFTERNOON are a minimal pair as they have identical handshape and movement but differ in their location (Sutton-Spence & Woll, 1999). Signed languages are therefore composed of signs with internal structure. Note that there are currently several competing models of sign phonology (e.g., Brentari, 1998; Sandler & Lillo-Martin, 2006), but in the current research we are dealing with a level of detail that these models agree on, namely, with the primary sign parameters of location, movement, handshape, and orientation (see, for example, Brentari, 1998), and with a level of detail that allows us to assume crossover from work on ASL to BSL. In this respect we follow several previous investigations of online processing in various sign languages (e.g., Catalan: Baus, Gutierrez-Sigut, Quer, & Carreiras, 2008; Spanish: Carreiras, Gutierrez-Sigut, Baquero, & Corina, 2008; American: Corina & Emmorey, 1993; Corina & Knapp, 2006; Emmorey & Corina, 1990; British: Dye & Shih, 2006).

The location parameter appears to be especially important in sign processing. It is the first parameter to be identified in gating (Emmorey & Corina, 1990); it consistently produces inhibition in priming studies (Carreiras et al., 2008; Corina & Emmorey, 1993; Corina & Hildebrandt, 2002); it is the parameter that is acquired first by children (Meier, 2000; Morgan, Barrett-Jones, & Stoneham, 2007); and it is the least affected parameter in acquired language impairment (Corina, 2000) and in misperception errors (Orfanidou et al., 2009). The question we ask here, then, is what role location information and especially transitional movements between locations play in sign segmentation. As we will argue below, there are several sources of information used in sign segmentation. In the current study, however, we investigate the impact of location information because of its primacy in previous psycholinguistic investigations.

There are two ways a sign can include a transitional movement between two locations. The first type is not a transition between locations but instead occurs within a single sign as a handshape change. As a sign is articulated, the handshape could begin as one configuration and finish as another (for example the sign starts with a closed hand and finishes as open). We do not investigate these types of transitions here. The second type of transition (and the one we investigated) is between two locations in a sequence of signs. One sign is articulated and then, for the next sign, the action moves to another location. Because we are interested in the segmentation of signs in continuous signing, we focus in the current set of studies on the effect of transitional movements between locations in sign sequences.

Transitions as modality-specific segmentation cues

A characteristic of BSL and other signed languages is the existence of salient visual gaps occurring between individual signs in signed sequences. For example, in the BSL sentence MAN WANT EAT, "the man wants to eat", the hands move from the chin to the trunk and back to the chin. There are transitional movements between the first and second sign and between the second and third sign. These transitions between spatial locations may be one of the reasons why sign is slower than speech (Emmorey, 2002). Transitions provide potentially very useful cues to the temporal locations of sign boundaries in the input sign stream: If sign comprehenders can identify and temporally locate a transition, then they would know that a new lexical sign is likely to be about to start.

If transitions provide explicit sign-boundary cues in this way, then recognition of a sign following a large and visually salient transition from another sign in a distant location should be easier than following another sign in the same location. If this recognition difference were found, it would suggest that sign segmentation is based (at least in part) on a modality-specific principle. The phonological parameters of a sign (i.e., location, handshape, movement and orientation) are produced with temporal overlap, whereas the phonological components of speech are expressed in a much more sequential fashion. This means that sign language can be characterized as appearing over time as a sequence of clusters of parameters appearing more or less in parallel but often separated by transitional movements, whereas speech appears over time as a more serial sequence of sounds. Vocal-tract articulators do of course have to move from one place of articulation to another between speech sounds, but there is nothing to distinguish transitions between sounds within words unambiguously from transitions between sounds across word boundaries. In addition, the speech articulators move very small distances and are often invisible to the interlocutor. Transitional movements in speech therefore cannot signal word boundaries in the way just hypothesized for sign language. So if sign transitions were to signal boundaries in the way just proposed, then this kind of segmentation would be something special to sign language.

Note, however, that sign segmentation cannot be based only on the use of transitional boundary cues, since there would then be no way to segment two signs produced in the same location. In addition, a transition to a following sign can include not only a change in the location features, but also a change in selected fingers, configuration, orientation, or in manner of movement, or a combination of these. For the purposes of the current research, however, we focus on the effect of location changes on sign segmentation, while trying to control for changes in other features of the signs (see the Methods section). Note also that there may be other modality-specific ways in which signs are segmented which are not considered here (e.g., segmentation based on a spatial frequency analysis of the sign stream or movements of the head and/or eyes). The question, therefore, is whether segmentation based on transition-cued boundaries complements other sign-segmentation procedures or whether there is no such modality-specific segmentation procedure.

Transitions as modality-general segmentation cues

An alternative possibility, however, is that sign transitions provide information which can be used by modality-general procedures. On this view, sign segmentation would work like speech segmentation. How then is speech segmented? The consensus is that spoken-word recognition is based on the simultaneous evaluation of multiple lexical hypotheses and competition among those hypotheses (see, for example, McQueen, 2007 for a review). Segmentation emerges out of this evaluation and competition process (that is, boundaries between words are found as the recognition system settles on the best lexical hypothesis for each part of the continuous input). Multiple sources of information (e.g., from metrical structure, Cutler & Norris, 1988; phonotactics, McQueen, 1998; and acoustic fine detail, Gow & Gordon, 1995) can influence the segmentation process by probabilistically cueing the location of likely word boundaries, and those multiple cues may vary in their efficacy (Mattys, White, & Melhorn, 2005), but the core mechanism that they feed into is still that of competition among multiple lexical hypotheses.

Sign recognition may indeed be based on this kind of evaluation and competition process. In a series of lexical decision and priming experiments, Carreiras et al. (2008) showed that recognition of signs in Spanish Sign Language is influenced by the signs' lexical neighbourhoods (i.e., the number of signs with the same location or handshape parameter as the target sign). Facilitatory neighbourhood effects were taken to reflect the process of accessing multiple signs, and inhibitory neighbourhood effects were taken as evidence of competition among those signs. In Experiment 1 we ask whether sign transitions influence BSL segmentation by modulating this sign competition process.

Analytically, transitional information could help sign comprehenders constrain sign competition by narrowing the lexical search space. Consider the situation where there is a large transition from one sign to another. Here, as the transition begins, many signs may follow (all signs with a location different from the starting location; e.g., for a transition starting from a sign on the head, all signs lower than the head). If, in contrast, there is no transition to a different location, then the locational search space is maximally constrained: the next sign must be in the same location. This hypothesized use of transitional information to determine which signs are part of the lexical competition process is equivalent to the use of acoustic-phonetic information to constrain spoken-word recognition. In the Cohort model of speech recognition (Marslen-Wilson, 1987), the cohort of lexical candidates is gradually narrowed down to one winning candidate as acoustic-phonetic information rules out phonetically non-matching candidates. Similar processes constrain the competition process (and hence word segmentation and recognition) in other models, including TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994; Norris & McQueen, 2008). Thus, if transitional information constrains sign segmentation by narrowing the lexical search, then this would be evidence of a modality-general procedure. Previous research has indeed pointed to modality-independent processes in sign-language segmentation (Orfanidou et al., 2010). Very little is understood, however, about the role of transitions in sign segmentation, and hence it is not clear whether they too will be treated in a modality-general way.

Predictions

In Experiment 1 we therefore tested whether transitions have a modality-specific or a modality-general effect on sign segmentation. The two accounts make opposite predictions. On the one hand, if transitions provide modality-specific explicit sign-boundary cues, then signs should be easier to segment and recognize after large transitions than when there is no transition. On the other hand, if transitions narrow lexical search in a modality-general fashion, then signs should be harder to segment and recognize after large transitions than when there is no transition.

We predicted that transitions would have a modality-general effect, for two related reasons. First, evidence over the past 30 years or so on different signed languages has demonstrated that remarkably similar patterns exist across the speech and sign modalities, both at the behavioural level (Emmorey, 2002; Klima & Bellugi, 1979; Meier, 2000) and at the neural level (Corina, San Jose-Robertson, Guillemin, High, & Braun, 2003; MacSweeney et al., 2002; Petitto et al., 2000). Second, and more specifically, our recent work has already suggested that sign segmentation is based on modality-general principles (Orfanidou et al., 2010). In particular, research in speech segmentation has indicated that listeners segment speech so as to avoid impossible words (Norris, McQueen, Cutler, & Butterfield, 1997). To do so, they make use of a Possible Word Constraint (PWC): lexical parses that include impossible words are disfavoured in the lexical competition process (Norris et al., 1997; Norris & McQueen, 2008). Evidence for the PWC has been found in a range of typologically diverse spoken languages (English: Norris et al., 1997; Dutch: McQueen & Cutler, 1998; Japanese: McQueen, Otake, & Cutler, 2001; Sesotho: Cutler, Demuth, & McQueen, 2002; Cantonese: Yip, 2004; Slovak: Hanulíková, McQueen, & Mitterer, 2010; and German: Hanulíková, Mitterer, & McQueen, 2011). It appears that a lexical viability constraint also operates in BSL segmentation. Deaf signers of BSL found it easier to spot real BSL signs in nonsense contexts when the context was a possible BSL sign than when it was not (Orfanidou et al., 2010).

In spite of this evidence for modality-general sign segmentation, it was still possible, however, that transitions could have a modality-specific effect. Large transitions between signs are highly salient, so could easily act to demarcate sign boundaries. This was indeed the initial intuition of the third and fourth authors (native and fluent BSL signers respectively). Furthermore, the fact that lexical viability constraints appear to be used in BSL segmentation in a modality-general way (Orfanidou et al., 2010) does not entail that transitions will be treated similarly.

In Experiment 1 we therefore asked Deaf signers of BSL to try to spot real BSL signs in nonsense-sign contexts. This sign-spotting task is the analogue of the word-spotting task used in speech-segmentation research (Cutler & Norris, 1988; McQueen, 1996) and has already been used successfully in research on BSL (Orfanidou et al., 2010). There was either a minimal transition between the nonsense context sign and the following target sign, or a physically small or large transition (see below for details). According to the modality-specific (boundary cue) hypothesis, the large-transition condition should be the easiest; according to the modality-general (lexical search) hypothesis, however, this should be the hardest condition.

Within the small- and large-transition conditions, we also manipulated the nature of the transitions, such that they were made either within a major location (Battison, 1978; Brentari, 1998) or across two major locations. According to Brentari, there are five major locations: head, trunk, arm, non-dominant hand, and neutral space. One important generalization with respect to the location parameter is that the major body area (e.g., the head) remains constant within a sign, but different subareas (e.g., the chin, forehead) can be combined within that sign if it is a compound sign (a single lexical sign derived from two different lexical signs e.g., MAN, WOMAN are combined with some articulation reductions in the single sign PEOPLE). This observation is often referred to as Battison's Place constraint: "There can be only one major body area specified in a sign" (Sandler & Lillo-Martin, 2006, p. 138). There are some exceptions to this constraint, in both ASL and BSL, especially where two signs have become a compound. In both sign languages, however, the constraint is a phonotactic preference that applies to the majority of signs in the lexicon (Hohenberger, 2007; Sutton-Spence & Woll, 1999; see also Orfanidou et al., 2009). Since listeners use phonotactic knowledge to segment speech (McQueen, 1998; Suomi, McQueen, & Cutler, 1997), and since BSL signers show evidence of using such knowledge in sign recognition (Orfanidou et al., 2009), it was possible that signers also use this knowledge in segmentation. If so, they should be faster to spot real signs when the transition involves moving to a different major location (since there must be a sign boundary at this point) than when the transition involves moving to another subarea within the same major location (which could be a within-sign transition). This would be evidence of another kind of modality-general segmentation procedure, analogous to that demonstrated in speech, where a word is easier to spot when phonotactics require there to be a syllable boundary at the word's edge than when there is no phonotactically necessary boundary (McQueen, 1998; Suomi et al., 1997).

The possibilities of segmentation based on competition and on phonotactics are not mutually exclusive, so it was possible that we would observe an effect of the narrowing of the lexical search space (large transitions worse than small transitions worse than minimal transitions) and of phonotactic knowledge (within-location transitions worse than between-location transitions). Similarly, segmentation based on transitional boundary cues and on phonotactics are not mutually exclusive, so it was possible that we could observe a boundary effect (large transitions better than small transitions better than minimal transitions) and a phonotactic effect.

Age of acquisition

When studying signed language processing, a crucial factor to take into consideration is the language learning experience of the Deaf participants. Because 90–95% of Deaf children are born to hearing parents who do not sign, native-like language acquisition which results from early and consistent exposure to a language is not the norm. Previous work has demonstrated that age of exposure to sign language results in subtle but measurable differences in processing (Carreiras et al., 2008; Corina & Hildebrandt, 2002; Mayberry & Fischer, 1989; Newman et al., 2002; Newport, 1990). During sentence recall and shadowing, for example, late learners of ASL produce a disproportionate number of phonological substitutions (i.e., signs that are phonologically similar to the target signs but differ in meaning) relative to native signers (Mayberry, Lock, & Kazmi, 2002). Mayberry (1994) has interpreted this phenomenon as evidence that delayed learners of ASL focus more attention on the phonological form of signs than native or early learners because they find phonological processing more difficult (i.e., late learners have a "phonological bottleneck").

In the present study, therefore, we included age of sign-language acquisition as a between-participant factor. In our previous work on sign segmentation using the word-spotting task, however, we did not find a significant effect of age of acquisition (AoA) (Orfanidou et al., 2010). For this reason, we decided that it would be sufficient in the present experiments to distinguish between only two groups of signers based on AoA: those who learnt BSL from birth to 5 years of age and those who learnt BSL after the age of 5 years. This allowed us to ask if the phonological bottleneck affects ease of sign segmentation. We expected the native/early group to be, overall, faster and more accurate than the late learner group. In addition, it was conceivable that the late learners of BSL, experiencing a phonological bottleneck, would need to work harder to be able to make segmentation judgements. If so, transitions between signs could be found to be more important for cueing segmentation for them than for the native signers and early learners of BSL.

EXPERIMENT 1

Method

Participants

A total of 39 Deaf BSL signers between the ages of 18 and 50 years took part. Of these, 23 were native/early Deaf BSL signers (exposed to sign before 5 years of age, 19 out of the 23 had Deaf parents), and 16 were late BSL learners (exposed to sign after 5 years of age and before 16 years of age). All had normal or corrected-to-normal vision. We used the Raven's Matrices test of cognitive abilities (Raven, 1938) to evaluate nonverbal cognitive abilities. All participants scored within the normal range on this test. Each participant completed a questionnaire about his or her sign-language exposure (e.g., parents' level of signing, extent of mixed/sign used in the home, etc.), socio-economic background and academic qualifications, including level of English fluency.

Materials

The stimulus set consisted of 96 monosyllabic and monomorphemic BSL signs, including mostly nouns and verbs (see Appendix A). It was split into three groups of 32 signs. These groups were matched on familiarity (on a scale from 1 to 7, 7 being very familiar; Vinson, Cormier, Denmark, Schembri, & Vigliocco, 2008), location neighbourhood size, and handshape neighbourhood size. As we were not controlling for phonological structure beyond particular handshapes and locations, the neighbourhood estimates for location and handshape were obtained using the same dictionary method as in Carreiras et al. (2008). This method entails counting how many signs in the BSL dictionary (British Deaf Association, 1992) were articulated in each possible location in BSL (20 distinct locations). Location neighbourhood ranged from 3 to 1022 signs. This last number refers to the many signs in BSL that are specified as occurring in neutral sign space (somewhere in front of the body). These signs are in fact articulated at different heights (e.g., upper or lower neutral space). Because of the lack of a detailed phonological description of this particular location in BSL (or indeed in any signed language; Sandler & Lillo-Martin, 2006), we included only 6 signs with this location (2 signs in each of the three groups of 32 signs). For handshape, the neighbourhood estimates were obtained by counting how many signs in the BSL dictionary were articulated with each specific handshape (58 handshapes; range: 1–285 signs). A one-way ANOVA, where group was entered as a fixed factor and familiarity, location neighbourhood and handshape neighbourhood were the dependent variables, showed no difference between groups on any of these variables (familiarity, F (2, 126) = 1.3, $p = .246$: location neighbourhood, $F < 1$; handshape neighbourhood, $F < 1$). Over all groups (96 signs), mean familiarity was 5.6, mean location neighbourhood was 118 signs, and mean handshape neighbourhood was 90 signs.

Following word-spotting methodology (McQueen, 1996), we created three preceding nonsense contexts for each sign in each group, one context with a minimal transition between the real BSL sign and the preceding nonsense sign, one with a small transition (less than 20 cm) and one with a large transition (greater than 20 cm). The term “minimal transition” means that there was no transition to a different location, but that there could be a change of state in some of the other parameters (handshape, orientation) and/or a re-articulation of the approach to that location. Note that the distances of smaller or larger than 20 cm were chosen to be small and large relative to the body size of the signer, but that we are not making any absolute claim that the cut-off between small and large transitions is always precisely 20 cm.

In each of the three groups of target signs, half of the non-minimal transitions ($n = 16$) took place within the same major body location, for example, transitions from the lower arm to the target POLICE, located on the wrist (small transition) or from the upper arm (large) to the target POLICE, located on the wrist (large transition). These will be referred to as “within transitions”. The other half of the non-minimal transitions were across body locations (“across transitions”), for example, transitions from the neck/throat to the target YESTERDAY, located on the cheek (small transition) or from the stomach to the target YESTERDAY, located on the cheek (large transition). Transitions within the head, the trunk, and the arm were considered as “within” transitions, while transitions across these areas were considered as “across” transitions. A transition within the neutral space (low, middle, high) was considered as a “within” transition. In Figure 1 we provide an example of a minimal-transition stimulus. In Figure 2(a–b) we provide an example of a small transition within the same location and in Figure 2(c–d) a large transition within the same location. Figure 3(a–b) shows a small transition across locations and Figure 3(c–d) shows a large transition across locations. A detailed description of all nonsense contexts can be found http://www.ucl.ac.uk/dcal/documents/transitions_supplementary_materials/

To ensure that the nonsense contexts were similar in all other respects apart from the transition, the three nonsense contexts (minimal transition, small transition, large transition) had the same handshape, movement, and orientation, and were matched in location neighbourhood size. The inclusion of the minimal-transition nonsense context meant that all nonsense contexts were essentially matched in location neighbourhood size to the real BSL sign to which they were paired. Due to other restrictions in creating the nonsense contexts described above (i.e., the requirement to use different locations in order to achieve small and large transitions, within or

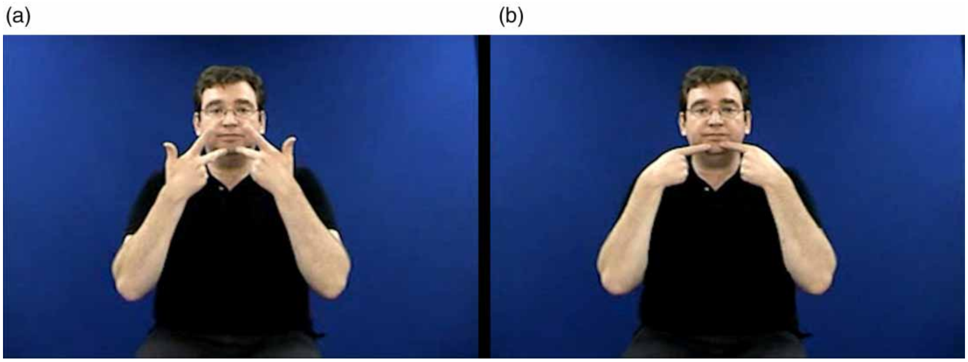

Figure 1. *Example of a minimal-transition stimulus. The nonsense context is articulated on the cheek (a); the target sign ANNOUNCE follows, which is also articulated on the cheek (b). Note the handshape change between nonsense context and target stimulus.*

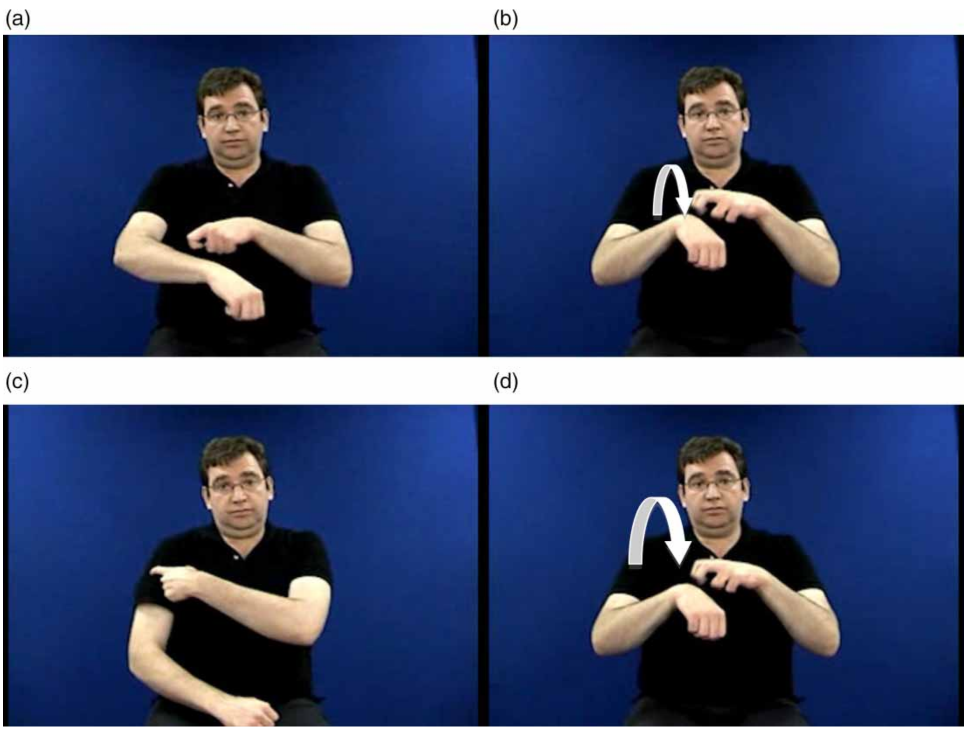

Figure 2. *Example of a transition within the same location, small (a–b) and large (c–d). In (a), the nonsense sign is articulated on the lower arm, followed by the real target sign POLICE (b), which is articulated on the wrist. In (c), the nonsense sign is articulated on the upper arm, followed by the real target sign POLICE, articulated on the wrist (d). Note the handshape change between nonsense context and target stimulus.*

across) we included transitions from a higher to a lower location neighbourhood, or vice versa, in only 12 cases (see Supplementary Material).

With regard to the differences between the nonsense context and the target sign (apart from the location change depending on the condition),

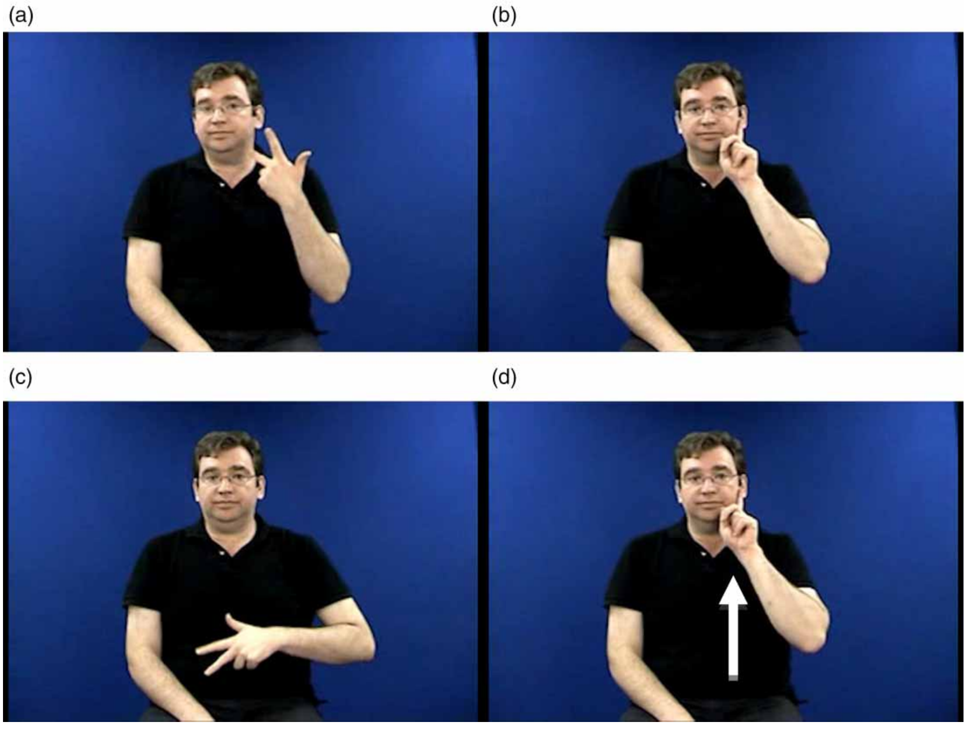

Figure 3. *Example of a transition across locations, small (a–b) and large (c–d). In (a), the nonsense sign is articulated on the lower neck, followed by the real target sign YESTERDAY (b), which is articulated on the cheek. In (c), the nonsense sign is articulated on the stomach/lower trunk, followed by the real target sign YESTERDAY, which is articulated on the cheek (d). Note the handshape change between nonsense context and target stimulus.*

almost all pairings of nonsense contexts and target signs included a handshape change (apart from six stimuli: CAT, CHEESE, CULTURE, COMPLAIN, JUMPER, WRISTWATCH), that is, the target sign had a different handshape to that used in the three contexts for this particular target. Importantly, the handshape change was present and was the same in all the types of nonsense context for a particular target, so that if the change of handshape is used as a cue for segmentation, then it could be used equally across all the conditions of the experiment. As mentioned in the previous paragraph, the handshape was the same for all the types of nonsense context for a particular target (see Figures 1–3 and Supplementary Material). With respect to the movement, the nonsense context had a different movement than the target sign in most of the stimuli ($n = 69$). With respect to orientation, the nonsense context had a different orientation than the target sign in half of the stimuli ($n = 49$). Figures 1–3 portray an example in which the movement and orientation of the target sign and the nonsense context are the same but the handshape is different. It is critical to note that, even if these changes in handshape, movement and orientation between the nonsense context and the target sign could be used to signal a change in the lexical sign (and, hence, a sign boundary), they could be used in all the conditions *equally* (minimal transition, small transition within/across, large transition within/across) as they were present in all these types of nonsense contexts. The only way in which the nonsense contexts were different was with respect to the presence and type of location transition. These differences between the nonsense contexts and the target signs were unavoidable as it would be impossible to create nonsense contexts that are non-existent signs and are articulated in the same location (for the minimal transition), and have the same movement and orientation as the target sign. It would be potentially possible for the transition conditions (as the location would be different), but then we would introduce a difference between our experimental conditions (no change in movement, orientation or handshape between target and nonsense context in the transition conditions, but a change in some or all of these parameters in the minimal-transition condition).

All the nonsense signs were evaluated by four native Deaf signers as to whether they were indeed non-existent signs in BSL and its regional dialects, and any signs which were not unanimously accepted as being non-existent were excluded. All the nonsense contexts included only one location, 4 included a repetition of movement, 7 included a hand internal movement, and they were all non-existent but phonologically possible combinations of handshape, location and movement.

The three groups of real BSL signs were rotated across each of the different conditions (minimal transition, small transition, large transition) and were paired with the appropriate nonsense context for each condition, creating a three-version experiment for presentation to three sets of participants. Each participant saw all 96 targets only once: 32 embedded in a minimal-transition nonsense context, 32 embedded in a small-transition nonsense context, and 32 embedded in a large-transition nonsense context. Thus, for participant X in version 1, targets 1–32 would appear combined with a minimal transition, targets 33–64 would appear combined with a small transition, and targets 65–96 would appear with a large transition. For participant Y in version 2, targets 1–32 would appear with a large transition, targets 33–64 with a minimal transition, and targets 65–96 with a small transition. In version 3, participant Z would see targets 1–32 with a small transition, targets 33–64 with a large transition, and targets 65–96 with a minimal transition. The actual order in which these targets appeared in each version of the experiment was randomized. A total of 136 fillers, consisting of 2 nonsense signs, were pseudo-randomly mixed with the target-bearing stimuli. The only difference between the three versions lay in the contexts in which the targets appeared. The nonsense fillers were non-existent combinations of phonological parameters but, in contrast to the nonsense contexts, they included a larger variety of combinations (e.g., two locations, two path movements, combination of internal movement with path movement, repetition of movement, etc.).

A Deaf native BSL signer (the third author) practised each sign in isolation and then produced them in the prescribed two-sign sequences (nonsense-target for experimental sequences, nonsense-nonsense for filler sequences).The materials were filmed in a professional filming studio and clips were then edited into separate files using iMovie software. Videos with examples of stimuli are available (see http://www.ucl.ac.uk/dcal/documents/transitions_clips/).

Procedure

Each session started with a practice block, during which it was made clear to the participants that the targets were simple, frequent signs and that no lexical compounds, or signs which describe location and movement of entities (i.e., classifiers), were included in the experiment. The practice was followed by one version of the main experiment, which was split into two blocks. The stimuli were presented on a 19-inch computer screen using DMDX software (Forster & Forster, 2003). Each trial lasted 4 s, with 2 s between the onsets of the stimuli. Participants were asked to press the right-button (green) on a button-box if they saw a real BSL sign and then to sign to a camera in front of them what the sign was. No response was required if participants did not spot a real BSL sign. The experiment lasted approximately 20 minutes.

RESULTS AND DISCUSSION

Analyses of variance (ANOVAs) by participants (*F*1) and items (*F*2) were performed for reaction times (RTs) and error rates. Mean RTs measured

Table 1. *Experiment 1: Mean reaction time (RT, in ms, from video onset) and mean error (proportions) in each context condition (standard errors in parentheses) for the two groups of participants*

		Small transition			Large transition		
	Minimal transition	*Overall*	*Within*	*Across*	*Overall*	*Within*	*Across*
Native/early learners							
RT	2278 (60.9)	2363 (57)	2417 (52.9)	2308 (60.3)	2385 (58.2)	2417 (54.7)	2353 (59.3)
Error	.11 (.02)	.13 (.02)	.16 (.03)	.11 (.03)	.15 (.03)	.19 (.03)	.11 (.02)
Late learners							
RT	2258 (73.1)	2385 (68.6)	2407 (63.4)	2363 (70.8)	2416 (70.2)	2467 (61.9)	2365 (69.3)
Error	.17 (.03)	.14 (.03)	.19 (.04)	.10 (.02)	.19 (.03)	.22 (.03)	.15 (.03)

from video onset and mean error rates are shown in Table 1. We also include additional analyses of the RTs from video onset where the number of video frames was entered as a covariate. We thus report an analysis of RTs from video onset (see also Orfanidou et al., 2010) and an analysis of RTs from video onset with the number of video frames as a covariate. A similar pattern of results was found in a third analysis with RTs from target onset. The results of this analysis are given in Appendix B. We opted for analyses from video and target onset instead of an analysis from video offset that is often used in spoken-word-spotting experiments (McQueen, 1996) as we wanted to minimize the effect of the duration of the nonsense context on the participants' RTs. Video duration can only be estimated, since actual playing times may vary across trials (J. Forster, personal communication, 26 June 2009). Convergence between the three analyses is critical to ensure that any differences between conditions are real and not an effect of different video durations between conditions.

Such durational differences were indeed present. The average number of frames was 70 in the minimal-transition condition (~2329 ms, $SD = 5.4$, $MIN = 53$, $MAX = 86$), 74 in the small-transition condition (~2487 ms, $SD = 6.6$, $MIN = 60$, $MAX = 89$), and 75 in the large-transition condition (~2466 ms, $SD = 6.7$, $MIN = 57$, $MAX = 95$). An ANOVA showed that there was a significant difference between conditions in the number of frames (F (2, 190) = 38.2, $p < .001$). Pairwise comparisons showed that the minimal-transition stimuli had fewer frames than the small- (mean difference = −4 frames, $p < .001$) and large-transition stimuli (mean difference = −4 frames, $p < .001$). There was no difference in the number of frames between the small and large transitions (mean difference = 1 frame, $p = .837$). In the transitions conditions, an ANOVA with the factors Size (small vs large) and Type (across vs within) revealed that there was no difference in frames between within and across transitions (effects of Size, Type, and Size x Type, all Fs < 1). The average number of frames was 74 for transitions both across and within major body locations (small transitions within: $SD = 6.1$, $MAX = 87$, $MIN = 60$; small transitions across: $SD = 7.1$, $MAX = 89$, $MIN = 60$; large transitions within: $SD = 5.9$, $MAX = 89$, $MIN = 57$, large transitions across: $SD = 7.5$, $MAX = 95$, $MIN = 64$). These differences in duration across conditions underline the need for convergent evidence across the different RT analyses.

Analyses from video onset and analyses of covariance

In the by-participant analyses, Context was included as a within-participants factor with three levels: minimal transition, small transition, and large transition. Version was included as a between-participants factor. In the by-item analyses, Context was included as a within-items factor, with three levels (minimal transition, small transition, and large transition). In both participants and items analysis, Group was included as a between-participants

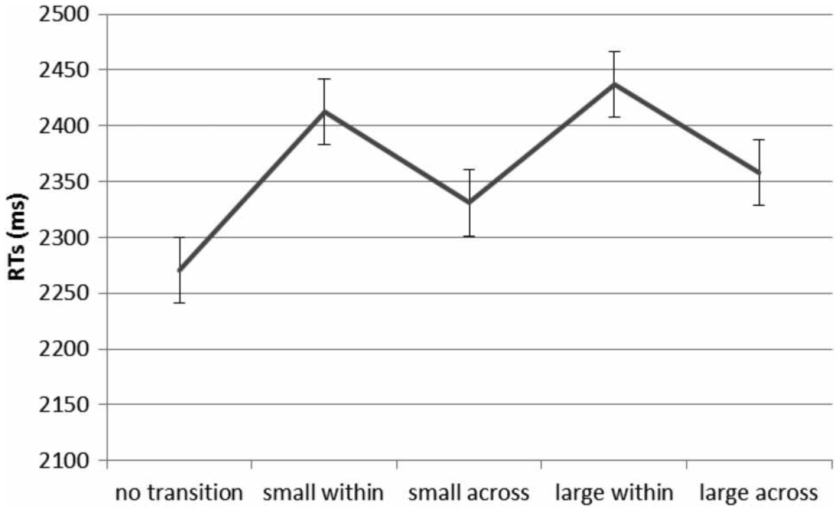

Figure 4. *Mean reaction time (RT, in ms, from video onset) collapsed for the two groups of participants in each context condition. Error bars represent one standard error.*

factor, with two levels (Native/Early learners, Late learners). For the Analyses of Covariance (ANCOVAs), we performed univariate ANOVAs in which response times (or error rates, for the analysis of the errors) were entered as the dependent variable, Context and Group were entered as fixed factors, and Number of Frames was entered as a covariate. Two items with disproportionate error rates across all versions of the experiment (above 65% error rate) were excluded from the analyses. Trials where participants pressed the button but then failed to sign the correct target to the camera (item 53; 1.4% of target-bearing trials) were treated as errors. No outlier (very fast or very slow) RTs were trimmed prior to statistical analysis. The significance level adopted in this study is $p < .05$. An effect is treated as significant when $p < .05$ was found for all three F-values ($F1$, $F2$, and min F').

Latencies

There was no effect of Group either as a main effect ($F1$, $F2 < 1$) or as an interaction with Context ($F1$, $F2 < 1$). There was a main effect of Context ($F1$ (2, 66) = 14.7, $p < .001$, $F2$ (2, 554) = 18.2, $p < .001$, min F' (2, 200) = 8.1, $p < .001$), suggesting differences in performance as a function of the transition condition. The ANCOVA showed a main effect of Context ($F2$ (3, 554) = 18.6, $p < .001$), a main effect of number of frames ($F2$ (1, 553) = 6.2, $p = .013$) and a main effect of Group ($F2$ (1, 554) = 6.8, $p = .009$) but no interaction between Group and Context ($F2 < 1$). Pairwise comparisons with Bonferroni correction showed a significant difference between the Minimal and Small Transition (mean difference = −104.5, $p < .001$) and the Minimal and Large Transition (mean difference = −131.3, $p = .001$). There was no difference between Small and Large transitions (mean difference = −26.8, $p = 1.0$). As shown in Figure 4, participants were faster for the minimal transitions than the small and large transitions, and faster for the small than large transitions, although this latter difference did not reach significance.

The above analyses revealed differences between the minimal-transition context and the contexts in which there was either a small or large transition but, because type of location change (within vs across location) does not apply to the minimal-transition condition, these analyses necessarily ignored the type of location change. Additional t-tests were therefore carried out comparing the minimal-transition condition, first with the within-location transitions and then with the across-location transitions. These tests showed that, for transitions within the same location, responses to signs with minimal transitions were significantly faster than those to signs with small and large transitions (minimal transition vs small within, $t1$ (38) = 3.8, $p = .001$, $t2$ (91) = 3.7, $p < .001$; minimal transition vs large within, $t1$ (38) = 4.3, $p < .001$, $t2$ (92) = −5.9, $p < .001$). But when the transitions were across locations, the difference was significant only for large transitions (minimal transition vs small across, $t1$ (38) = 1.5, $p = .155$, $t2$ (90) = −2.7, $p = .008$; minimal transition vs large across, $t1$ (38) = 2.5, $p = .019$, $t2$ (89) = 3, $p = .003$).

For a more detailed examination of the differences between the transition conditions, additional ANOVAs were performed in which the minimal transitions were not included. In these analyses, transition Size and transition Type were entered as within-participant factors with two levels (small vs large and within vs across respectively). Version and Group were entered as between-participant factors. There was no main effect of transition Size (small vs large, $F1$ (1, 33) = 4.1, $p = .052$, $F2$ (1, 365) = 4.9, $p = .027$, min F' (1, 105) = 2.2, $p = .138$), indicating that participants were not faster at sign-spotting when there was a small transition than when there was a large transition. The effect of transition Type was significant by participants only (within vs across, $F1$ (1, 33) = 26.3, $p < .001$, $F2$ (1, 365) = 3.0, $p = .084$, min F' (1, 396) = 2.7, $p = .101$), reflecting faster RTs for across-location transitions than within-location transitions. There was no interaction between transition Size and transition Type ($F1 < 1$, $F2$ (1, 365) = 1.9, $p = 0.164$, min F' (1, 46) = .301, $p = .585$), suggesting that the effect of transition type was not influenced by the size of the transition. Paired t-tests showed that the benefit from the major location change was present mainly for large transitions (see Table 1; small within vs small across, $t1$ (38) = 3.7, $p = .001$, $t2 < 1$; large within vs large across, $t1$ (38) = 4.1, $p < .001$, $t2$ (90) = 2.4, $p = .020$). In the participants analysis, there was a three-way interaction between Size, Type and Group ($F1$ (1, 33) = 5.4, $p = .026$, $F2 < 1$, min F' (1, 373) = 0.8, $p = .361$), reflecting the fact that the late learners group was slower than the native/early learners group for large transitions within the same location (2467 ms vs 2417 ms, see Table 1). Also, the native/early learners benefited more from a small transition across locations than the non-natives (see Table 1). This three-way interaction was not significant. There was no other effect of Group, either as a main effect or as an interaction with transition Size or Type (all Fs < 1). In the ANCOVA the effect of Size was no longer significant, but the effect of Type was now significant (Size, $F2$ (1, 364) = 2.4, $p = .120$; Type, $F2$ (1, 364) = 4.9, $p = .028$; Size by Type, $F2$ (1, 364) = 2.0, $p = .107$; Frames, $F2$ (1, 364) = 2.9, $p = .086$).

Errors

There was a main effect of Group by items only ($F1$ (1, 33) = 1.7, $p = .207$, $F2$ (1, 564) = 16.4, $p < .001$, min F' (1, 40) = 1.5, $p = .221$) but no interaction with Context ($F1$, $F2 < 1$). There was a significant main effect of Context in the participants and items analysis but not in min F' ($F1$ (2, 66) = 6.6, $p = .003$, $F2$ (2, 564) = 3.0, $p = .049$, min F' (2, 431) = 2.1, $p = .128$). In the ANCOVA, the effect of Context was still significant when the number of frames was entered as a covariate, while the effect of the number of frames was not significant (Context, $F2$ (2, 554) = 4.2, $p = .015$; Frames, $F2$ (1, 554) = 3.4, $p = .062$). The effect of Group was not significant ($F2$ (1, 554) = 2.9, $p = .086$) and there was no interaction with Context ($F2 < 1$).

Participants were more accurate in the minimal-transition condition than in any other conditions (minimal transition vs small transition, mean difference = −0.022, $p = .010$; minimal transition vs large transition, mean difference = −0.052, $p = .017$). Additional t-tests showed that participants were more accurate in the minimal-transition condition than the other transition conditions when this transition was within the same location (minimal transition vs small within, $t1$ (38) = −1.9, $p = .063$, $t2$ (95) = −3.6, $p < .001$; minimal transition vs large within, $t1$ (38) = −3.6, $p = .001$, $t2$ (95) = −5.1, $p < .001$; minimal transition vs small across, $t1$ (38) = 1.7, $p = .096$, $t2 < 1$; minimal transition vs large across, $t1 < 1$, $t2$ (93) = −1.5, $p = .128$). Unlike in the RT data, there was a significant difference in accuracy between the small- and large-transition conditions (more accurate on small transitions, mean difference = −0.031, $p = .016$). Overall, it seems that participants benefited more from a minimal transition or a transition across locations, especially if this was in the context of a small transition.

The analysis of the location-change conditions (i.e., excluding the minimal-transition condition) showed a main effect of transition Type (within vs across, $F1$ (1, 33) = 23.3, $p < .001$, $F2$ (1, 372) = 21.7, $p < .001$, min F' (1, 129) = 11.2, $p = .001$) but no effect of transition Size (small vs large, $F1$ (1, 33) = 5.8, $p = .022$, $F2$ (1, 372) = 1.9, $p = .172$, min F' (1, 297) = 1.4, $p = .232$). Participants were more accurate in spotting the real sign when there was a transition across locations than when there was a transition within locations (see Table 1). Similarly to the RT data, paired t-tests showed that this was true for both small and large transitions (small within vs small across, $t1$ (38) = 3.7, $p = .001$, $t2$ (93) = −2.8, $p = .006$; large within vs large across, $t1$ (38) = 3.9, $p < .001$, $t2$ (93) = −3.5, $p < .001$). The interaction between transition Type and transition Size was not significant ($F1$, $F2 < 1$).

In summary, Deaf signers of BSL were faster and more accurate in spotting real BSL signs embedded in nonsense-sign contexts when the nonsense signs were articulated in the same location as the real BSL signs than when there was a change of location. But each nonsense sequence in Experiment 1 was produced separately. Hence, the target signs in each of the three contexts were physically different. Possible differences in fluency, clarity or speed of articulation of targets across contexts could thus account for the differences in sign-spotting performance across conditions. Experiment 2 was run to control for this possibility. As in many spoken-word-spotting studies (e.g., Cutler & Norris, 1988) and a sign-spotting study (Orfanidou et al., 2010), the targets were digitally excised from their contexts and presented to new participants in a go/no-go lexical decision task, that is, participants had to press a button every time they saw a real BSL sign in a list of words and nonwords. We hoped to show that there would be no difference in lexical decision performance between signs taken from the different transition conditions.

EXPERIMENT 2

Method

Participants

A total of 19 native/early Deaf signers took part (12 with Deaf parents). None had participated in Experiment 1, and all had normal or corrected-to-normal vision. They were paid to take part.

Stimuli, design and procedure

Each of the target signs from Experiment 1 was excised from its context using iMovie software. We took as the starting point for the target the point in time at which the handshape of the target had been formed. Fillers were created by excising, using the same criterion, the second nonsense sign in each of the Experiment 1 fillers. The experiment was exactly analogous to Experiment 1 (i.e., same critical materials, design, and running order) except that each target and each filler was presented without its original context. The instructions of Experiment 1 were modified slightly: participants were asked to press the button whenever they saw a real BSL sign (they again signed the targets they detected to a video camera).

Results and discussion

Table 2 shows the mean RTs and mean error rates on lexical decisions in Experiment 2 to the Experiment 1 targets after the targets had been extracted from their contexts. In ANOVAs parallel to those in Experiment 1 there was, as predicted in this control experiment, no effect of the context from which the targets had been taken, either in RTs ($F1$, $F2 < 1$) or errors ($F1$ (2, 32) = 2.5, $p = .096$, $F2$ (2, 279) = 1.6, $p = .211$, min F' (2, 116) = 1.2, $p = .306$). The same was true when number of frames was entered as a covariate (RTs: Context, $F2$ (2, 278) = 1.3, $p = .271$; Frames, $F2$ (1, 278) = 9.9, $p = .002$; Error rates:

Table 2. *Experiment 2: Mean reaction time (RT, in ms, from target onset) and mean error (proportions) in each context condition (standard errors in parentheses)*

		Small transition			*Large transition*		
	Minimal transition	*Overall*	*Within*	*Across*	*Overall*	*Within*	*Across*
RT	1016 (68.3)	1035 (73.0)	1052 (73.3)	1017 (74.8)	1040 (67.5)	1073 (78.1)	1010 (60.9)
Error	.08 (.02)	.08 (.01)	.09 (.01)	.07 (.01)	.12 (.02)	.16 (.03)	.08 (.02)

Context, $F2$ (2, 278) = 1.2, $p = .303$; Frames, $F2$ (1, 278) = 1.7, $p = .196$). To directly compare the effects of Context in each of the two experiments, they were compared in an ANOVA with Context as a between-participant factor with three levels (minimal, small, large), and Experiment and Version as between-participant factors. The data for Experiment 1 included RTs from video onset and RTs from target onset. The effect of Context was significant (video onset, $F1$ (2, 104) = 9.1, $p < .001$, $F2$ (2, 674) = 5.6, $p = .002$; target onset, $F1$ (2, 104) = 43.4, $p < .001$, $F2$ (2, 674) = 5.3, $p = .005$) but importantly there was a significant interaction between Experiment and Context (video onset, $F1$ (2, 104) = 4.3, $p = .016$, $F2$ (2, 674) = 2.2, $p = .115$; target onset, $F1$ (2, 104) = 24.5, $p < .001$, $F2$ (2, 674) = 3.5, $p = .030$), indicating that the effects of context were different in the two experiments. Experiment 2 shows that the differences in the ease of spotting real BSL signs that had been embedded in minimal-transition contexts relative to those in small- and large-transition contexts were not due to differences in the way the real signs had been articulated in those different contexts.

GENERAL DISCUSSION

The aim of this research was to investigate whether the segmentation of a continuous stream of signing relies on modality-specific mechanisms or whether it follows modality-general principles that have already been identified for speech segmentation. Specifically, in Experiment 1 we tested whether transitional movements between locations in sign sequences (salient visual gaps between individual signs) provide information which can be used either by modality-general or by modality-specific segmentation procedures. We hypothesized that if transitions provide modality-specific explicit sign-boundary cues, then signs should be easier to segment and recognize after large transitions than when there are no such transitions between signs. However, if transitions constrain the lexical search space to within particular phonological neighbourhoods, in a modality-general fashion, then signs should be harder to segment and recognize after large transitions than when there is no transition.

We also asked if sign phonotactics are used, in a modality-general way, to guide segmentation. Specifically, we hypothesized that if sign comprehenders can use Battison's Place constraint ("There can be only one major body area specified in a sign"; Sandler & Lillo-Martin, 2006, p. 138), sign-spotting should be easier in the context of a transition across major body areas than in the context of a transition within a major body area. The change of location across major areas should signal that a sign boundary must be present.

The results point towards two modality-general effects stemming from, respectively, the lexicon or the phonotactic knowledge of the BSL users. First, minimal transitions were better than small or large transitions—because, we would argue, the absence of a transition to another location constrains the lexical search space to a specific sign location. In doing so, this information reduces the possible lexical candidates that the perceiver needs to consider, effectively by taking the location parameter out as a variable in the search. Second, transitions across major locations led to better sign-spotting performance than transitions within a major location. An across-location transition provides the cues of a sign boundary and thus guides segmentation. There was no evidence of a modality-specific transition effect that is unique to sign language (i.e., large transitions being best because they are the most salient boundary cues in the signal). Finally, Experiment 2 showed that the effects found in Experiment 1 were not due to physical differences in signs across contexts.

One issue that may seem problematic for drawing these conclusions concerns stimulus duration. The minimal transitions were shorter stimuli (as evidenced by the number of video frames) than the small or large transitions, and the effect of number of frames was significant in some of the covariance analyses. One might then argue that what the present results show is that the signers were modulating their response times based on the duration of the stimuli (e.g., waiting until the end of the stimulus to respond, or being able to identify signs earlier in shorter stimuli). But four aspects of the results refute this duration hypothesis. First, performance in sign-spotting was better in the minimal-transition condition compared to the other conditions also in the error rate data (i.e., not only in the response time data). In the accuracy data, according to the duration hypothesis, the physical duration of the stimuli should not affect performance. Second, participants were faster and more accurate for the across-location transitions compared to the within-location transitions even though there was no significant difference in the number of frames across these two conditions. Similarly, participants were more accurate for the small than for the large transitions even though there was again no significant difference in durations. If durational differences between stimuli were the sole cause of the observed differences in sign-spotting performance, no behavioural differences should have been found when there were no durational differences. Thirdly, and most importantly, the significant effects of context did not disappear in any of the analyses when number of frames was entered as a covariate. The main effect of number of frames appeared significant in only one of the covariance analyses. Thus, although there were durational differences between the stimuli in the different conditions, and these could potentially have influenced performance, we believe that a purely duration-based explanation cannot account for the present data. Lastly, the pattern of findings was remarkably consistent between the analysis on the RTs from video onset (where durational differences between the different contexts could have influenced the data) and the analysis from target onset, where the duration of the nonsense context had been subtracted from the RT data.

Transitions as modality-general cues: Restricting the lexical search space

A core mechanism in spoken-word recognition involves the evaluation of and competition among various lexical candidates. Once the best lexical candidate for each part of the continuous input has been established, the recognition system can use this information to identify boundaries between words. We propose then that sign recognition is based on evaluation and competition processes among multiple candidates. Indeed, other recent evidence has shown that sign recognition in priming studies is influenced by the signs' lexical neighbourhoods, as measured by the number of signs consisting of the same handshape or location (Carreiras et al., 2008). For low familiarity signs, a location with high neighbourhood density slowed down lexical decision responses, while a handshape with high neighbourhood density facilitated responses. In speech, acoustic-phonetic cues are used to constrain spoken-word recognition (Cohort model: Marslen-Wilson, 1987; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994; Norris & McQueen, 2008). In a similar way, information about the phonological components of the sign, and specifically location, could be used to constrain sign recognition. In the case where there is no location change (i.e., a minimal transition), the lexical search is more constrained than when there is a location change.

The fact that segmentation appears to benefit from shared location might appear to be at odds with other data from psycholinguistic studies on sign-language processing, indicating that the effects of shared location are inhibitory (e.g., Carreiras et al., 2008). There are several reasons for this difference, however, including the characteristics of the stimuli and the nature of the tasks (word-spotting vs lexical decision). With respect to the stimuli, it is important to note that the inhibitory effects of location in the Carreiras et al. (2008) study emerged for low familiarity signs (average 2.7 on a 7-point scale) but not for high familiarity signs (average 4.3). In the present study, average familiarity of the target signs was even higher (average 5.6). It is thus possible that the effects of location may be either facilitatory or inhibitory, depending on sign familiarity. With regards to the nature of the task, word-spotting requires segmentation, whereas lexical decision does not. It is conceivable that shared location could have a facilitatory effect on segmentation (by narrowing the lexical search space, as we have suggested) while it could have an inhibitory effect on lexical decisions to signs presented in isolation (because potential signs articulated in the same location are likely to be competing for recognition).

This importance of the location parameter in sign recognition is consistent with a number of previous findings. In gating studies the location parameter is identified first, followed by handshape and finally movement. In Tip Of the Finger states some information about location and handshape is available sooner than movement information (Thompson, Emmorey, & Gollan, 2005). Form-based priming studies in ASL (Corina & Emmorey, 1993) and Spanish Sign Language (Carreiras et al., 2008) reported inhibitory effects when targets shared an articulatory location with the primes. In these priming tasks, inhibition between signs that share the same location can be explained as competition between sign candidates activated early during sign access on the basis of their shared location feature. During sign recognition, identification of location thus occurs first and produces the initial cohort of candidate signs. Again, the inhibitory effects of phonological similarity are consistent with models of spoken-word recognition, which postulate a process of relative evaluation of possible lexical candidates (Luce & Pisoni, 1998; McClelland & Elman, 1986; Norris & McQueen, 2008).

Transitions as modality-general cues: Use of phonotactics

Transition information becomes meaningful for segmentation not as a simple visual cue to a sign boundary but when it is combined with other knowledge—either lexical knowledge, as when it narrows the lexical search, or phonotactic knowledge, as when Battison's Place constraint (Battison, 1978; Sandler & Lillo-Martin, 2006) appears to be engaged. Participants were faster to spot real signs when the transition involved moving to a different major location than when the transition involved moving to another sub-area within the same major location. It is not the case that two separate signs cannot be located in different parts of the same body area, therefore, transitions between signs within the same sub-area are still legal. But the problem is that single signs can move between locations in the same body area as well, making differentiation between a single- and a two-sign sequence more difficult. Critically, however, it cannot be the case that signed manual activity that moves across a major body area is made up of just a single sign. Once the sign moves to a new major area, the perceiver can infer that this must be a new sign. It seems that the proposed phonotactic constraints in the ASL literature have some psychological validity in BSL—signers use phonotactic knowledge to segment sign language, like listeners use phonotactic knowledge to segment speech. In other words, the violation informs the sign perceiver that there must be a sign boundary at the point of the violation. This argument is supported by analogous findings in the speech segmentation literature (McQueen, 1998; Suomi et al., 1997) that listeners find spoken words easier to spot when they are aligned with a syllable boundary containing a sequence of segments that would be phonotactically illegal within the syllable or word. Thus, although this particular application of phonotactics is unique to a visual phonology—the constraint concerns restrictions about signs in particular locations—it appears that this tendency reflects a modality-general segmentation procedure.

Alternative hypotheses

Let us consider other possible accounts of the present data pattern. One is that the signers' response latencies reflected differences in the duration of the stimuli across conditions. As we have already argued, there are four reasons to reject this hypothesis. Another alternative account is based on differences in shifts of visual attention across conditions. Such shifts are likely to take time, and thus one might argue that the longer RTs for targets with larger transitions may reflect longer attentional shifts. Again, there are four reasons to disfavour this hypothesis. First, it is based on the untested assumption that there are shifts of attention between consecutive signs. If the sign comprehender is attending to the linguistic message in each input sequence, and trying to spot real signs in those sequences, their attention does not need to shift (e.g., to some other message). Second, we would argue that the account based on modality-general segmentation procedures is more parsimonious than one in which segmentation is based on different mechanisms across modalities. Third, the time-constrained attention-shifting hypothesis offers no explanation for the error data (sign-spotting was more accurate in the minimal-transition condition). Fourth, this hypothesis offers no account of the difference between the within- and between-area results, where transition distance (and hence the hypothesized attentional shift time) was controlled. For these reasons we prefer the explanation based on the use of modality-general segmentation procedures.

Furthermore, it is important to emphasize that whatever the true explanation might be for the advantage of minimal transitions over larger transitions in sign segmentation, the present demonstration of this advantage is certainly evidence against the modality-specific hypothesis. If sign comprehenders used transitions as sign-specific boundary cues, they ought to have found it easiest to spot target signs when those boundary cues were strongest or most salient (i.e., the large transitions). This was not the case.

Age of acquisition

Finally, we note that there were no differences between groups in how they used the transitions. We had predicted that because late learners are more attentive to the phonological form of the signs (because of a "phonological bottleneck" in processing; Mayberry, 1994), they would appear to rely more on sign segmentation in cases where phonotactic information unambiguously signals a sign boundary. Contrary to this prediction, both groups benefited from a major location change. It is important to note, however, that this was not a pure saliency effect. If it were, then we should have observed effects of pure transition size. In other words, late and native/early learners did not prefer large transitions over small or minimal transitions. In this sense, the minimal transitions, which functioned to reduce lexical neighbourhood density, were robust sources of information which all signers, independent of their particular native skills with BSL, could use in segmentation. Related to this, an alternative explanation of the difference between within and across transitions would suggest that it reflects perceptual confusion of closely articulated non-sign and signs and has little to do with sign phonotactics and the one-place constraint. However, this account cannot provide a full explanation of the data. It would be difficult to assume that this factor comes into play only for the comparison of the within and across location transitions, but does not affect the minimal transitions, where perceptual confusion between the real and nonsense signs is most likely. This account, thus, wrongly predicts that performance should have been poorest in the minimal transition condition.

Conclusion

The present data add to a growing body of evidence for common language processing mechanisms irrespective of modality (Emmorey, 2002; Klima & Bellugi, 1979; Meier, 2000). They also extend our initial findings on sign segmentation, which suggested that language comprehension is guided by modality-general principles (Orfanidou et al., 2010). This is not to say that modality-specific mechanisms do not play a role in sign segmentation. Spatial-frequency analysis of the sign input or information from other parts of the sign (e.g., handshapes) could provide segmentation cues as well. What we have shown here, therefore, is that the transitions between different locations in space do not provide a modality-specific segmentation cue. To gain a better understanding of how signers recognize individual signs in continuous signing, future research should examine the interplay between, on the one hand, the modality-general mechanisms identified here and in Orfanidou et al. (2010), and, on the other hand, other possible segmentation mechanisms afforded to signers specifically by the visual-spatial modality of their language.

In summary, we have presented evidence that BSL users do indeed mind the gap in sign segmentation, not by using a modality-specific procedure based on larger gaps providing more salient sign-boundary cues, but rather by using at least two modality-general procedures. First, we have argued that sign comprehenders pay attention to the gap in the sense that the absence of a transition to another location helps them to narrow the lexical search space. Second, we have argued that sign comprehenders mind the gap as transitions can provide phonotactic cues to sign boundaries.

Supplemental material

Supplemental material for this paper can be found at http://www.ucl.ac.uk/dcal/documents/transitions_supplementary_materials/

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APPENDIX A

Experiments 1 & 2: 96 targets (real BSL signs)

ANNOUNCE, ARGUE, ARRIVE, ASK, BATTERY, BED, BELIEVE, BELT, BINOCULARS, BISCUIT, BREAD, BREATHE, BROWN, BUY, CAT, CHARMING, CHEESE, CHERRY, CHOCOLATE, COMPLAIN, CONFIDENT, COPY, COUGH, CRUEL, CRY, CULTURE, DEER, DEMAND, DONATE, DRILL, EASY, EAT, EMOTION, EVENING, FLOWER, GIRL, GOSSIP, GUILTY, HAPPY, HEARING-AID, HELP, ICECREAM, IGNORE, IMPORTANT, JACKET, JUMP, JUMPER, LOCK, LOOK, LOUD, LUCK, MORNING, MOTHER, MOUSE, NEW, PAPER, PARENTS, PERFUME, PLEASED, POLICE, POOR, PRINT, PRISON, RABBIT, RED, REFUSE, RELAX, RESPONSIBILITY, RIGHT, RUDE, SANDWICH, SCARF, SHAMPOO, SHOCK, SICK, SING, SKIRT, SMILE, SORRY, START, STRICT, SWALLOW, TELL, THINK, TIE, TIME, TOILET, TOMATO, TRANSLATE, TRUE, WANT, WATER, WIN, WORRIED, WRISTWATCH, YESTERDAY

APPENDIX B

Analyses from target onset

For this analysis, targets were excised from their context using iMovie software. We took as the starting point for the target the point in time at which the handshape of the target had been formed. The duration of these targets was used for the calculation of the target onset for the purposes of the analysis from target onset reported here (video duration − target duration = nonsense context duration). The resulting nonsense context duration was then subtracted from the raw RTs.

In the by-participant analyses, Context was included as a within-participants factor with three levels: minimal transition, small transition, and large transition. Version was included as a between-participants factor. In the by-item analyses, Context was included as a within-items factor, with three levels (minimal transition, small transition, and large transition). In both participants and items analysis Group was included as a between-participants factor, with two levels (Native/Early learners, Late learners). An ANCOVA including number of frames was also run.

Latencies

There was no effect of Group either as a main effect ($F1$, $F2 < 1$) or as an interaction with Context ($F1$, $F2 < 1$). There was a main effect of Context ($F1$ $(2, 66) = 98.5$, $p < .001$, $F2$ $(2, 554) = 18.9$, $p < .001$, min F' $(2, 601) = 15.9$, $p < .001$), suggesting differences in performance as a function of the transition condition. Pairwise comparisons with Bonferroni correction showed a significant difference between all types of transitions (all ps $< .001$, with the exception of minimal vs small in the by-items analysis, $p = .105$). As shown in Table B1, participants were faster for the minimal than large transitions, and faster for the small than large transitions. The ANCOVA showed a main effect of Context ($F2$ $(2, 552) = 16.4$, $p < .001$), no main effect of Group ($F2 < 1$), no main effect of Frames ($F2$ $(2, 552) = 1.6$, $p = .212$) and no interaction between Group and Context ($F2 < 1$). Pairwise comparisons with Bonferroni correction showed a significant difference between all types of transitions (all ps $< .001$, again with the exception of minimal vs small, $p = .303$).

A closer look at these differences revealed that the minimal-transition was faster than the large-transition condition rather than the small-transition (minimal transition vs small within, $t1$, $t2 < 1$; minimal transition vs small across, $t1$ $(38) = 1.4$, $p < .160$, $t2 < 1$; minimal transition vs large within, $t1$ $(38) = -5.4$, $p < .001$, $t2$ $(94) = -5.3$, $p < .001$; minimal transition vs large across, $t1$ $(38) = -2.9$, $p = .007$, $t2$ $(91) = -2.2$, $p = .029$).

The analysis on the location-change conditions (i.e., excluding the minimal-transition condition) showed a main effect of transition Size (small vs large, $F1$ $(1, 33) = 74.0$, $p = .052$, $F2$ $(1, 365) = 18.0$, $p < .001$, min F' $(1, 334) = 15.1$, $p = .002$) and a main effect of transition Type by participants only (within vs across, $F1$ $(1, 33) = 22.2$, $p < .001$, $F2$ $(1, 365) =$

Table B1. *Experiment 1: Mean reaction time (RT, in ms, from target onset) in each context condition (standard errors in parentheses) for the two groups of participants*

		Zero transition		*Small transition*		*Large transition*	
		Overall	*Within*	*Across*	*Overall*	*Within*	*Across*
Native/early learners							
RTs	1077 (58.9)	1139 (50.5)	1164 (59.1)	1111 (51.1)	1252 (57.7)	1306 (54.5)	1199 (63.2)
Late learners							
RTs	1092 (78.8)	1163 (70.9)	1155 (67.2)	1170 (80.1)	1266 (73.4)	1319 (77.6)	1213 (73)

3.2, $p = .076$, min F' (1, 389) = 2.8, $p = .095$), indicating that participants were faster at sign-spotting when there was a small transition and a transition across locations. In contrast with the previous analysis from video onset, there was a significant interaction between transition Size and transition Type ($F1$ (1, 33) = 17.6, $p < .001$, $F2$ (1, 365) = 5.1, $p = .024$, min F' (1, 315) = 3.9, $p = .047$), suggesting that the effect of transition type was influenced by the size of the transition. As shown in Figure B1, the difference between the two types of transition (across, within) was more pronounced in the large transitions compared to the small transitions. Paired t-tests showed that the benefit from the major location change was dependent on the size of the transition (small within vs small across, $t1$, $t2 < 1$; large within vs large across, $t1$ (38) = −4.8, $p < .001$, $t2$ (90) = −2.4, $p = .016$). There was no three-way interaction between Size, Type and Group ($F1 < 1$, although, numerically, the native/early learners benefited more from a small transition across locations than the non-natives, see Table B1) and no effect of Group, either as a main effect or as an interaction with transition Size or Type (all Fs < 1). The ANCOVA showed similar effects, that is, a main effect of Transition Size ($F2$ (1, 364) = 15.6, $p < .001$) and of Type ($F2$ (1, 364) = 6.9, $p = .009$). However, the interaction between Size and Type was no longer significant ($F2$ (1, 364) = 1.1, $p = .146$). The effect of Frames was not significant ($F2$ (1, 364) = 3.2, $p = .072$).

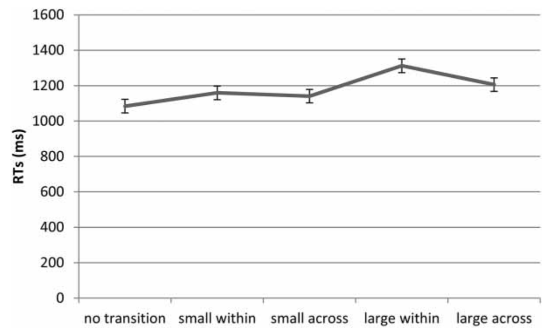

Figure B1. *Mean reaction time (RT, in ms, from target onset) collapsed for the two groups of participants in each context condition. Error bars represent one standard error.*