Full title:

Perceptual invariance or orientation specificity in American Sign Language? Evidence from repetition priming for signs and gestures

Short title:

ASL repetition priming

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<u>Language and Cognitive Processes</u> (Accepted for Publication)

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Abstract

Repetition priming has been successfully employed to examine stages of processing in a wide variety of cognitive domains including language, object recognition and memory. This study uses a novel repetition priming paradigm in the context of a categorization task to explore early stages in the processing of American Sign Language signs and self-grooming gestures. Specifically, we investigated the degree to which deaf signers' and hearing non-signers' perception of these linguistic or non-linguistic actions might be differentially robust to changes in perceptual viewpoint. We conjectured that to the extent that signers were accessing language-specific representations in their performance of the task, they might show more similar priming effects under different viewing conditions than hearing subjects. In essence, this would provide evidence for a visually-based "lack of invariance" phenomenon. However, if the early stages of visual action processing are similar for deaf and hearing subjects, then no such difference should be found.

In both groups, we observed robust effects of viewpoint, indicating that repetition priming for identical prime-target pairs was greater than in cases of categorization in which the prime and target varied in viewpoint. However, we found little evidence of group-related differences that could be interpreted as effects of perceptual invariance. These outcomes indicate that initial stages of sign and gesture recognition required for the categorization of action-types do not differ as a function of experience with a signed language. Instead, our data are consistent with and extend previously described visual-perceptual studies that have reported evidence for orientation-specific representations of human actions.

Keywords: sign language; ASL; deaf; repetition priming; linguistic processing; perceptual invariance.

Acknowledgements

This work was supported by National Institutes of Health–NIDCD Grant 2ROI-DC030910 to D. Corina and National Science Foundation (NSF) Grant SBE-0541953

1. Introduction

Signed languages of the deaf are naturally-evolving linguistic systems exhibiting the full range of linguistic complexity found in speech, but the field of sign language psycholinguistics is still in its adolescence. While most phenomena that form the foundation of our understanding of speech perception and production, such as lexicality and frequency effects, semantic- and form-based priming, categorical perception, production slips and tip-of-the-finger phenomena have been attested in sign languages (see Emmorey, 2002; Corina & Knapp, 2006, for recent discussions), there are currently no well-specified models of sign recognition and significant gaps in our knowledge of the processes involved in sign recognition remain.

A particularly glaring gap is our lack of understanding of how the initial stages of sign language processing differ from or are similar to stages of recognition that underlie human action recognition, something that the present study seeks to address. Lexical signs are composed of discrete human movements with conventionalized forms derived from fixed inventories of hand-shape postures, articulatory locations and movements (Stokoe, 1960). The perception of these forms may be considered a special case of the recognition of dynamic human form processing that underlies the interpretation of human actions in general. A comprehensive theory of sign language recognition will be enhanced by providing an account of when and how the processing of sign forms diverges from the processing of human actions in general. Recent neuro-imaging studies have reported differences in patterns of activation for signs versus non-linguistic gestures in deaf subjects (Corina et al, 2007; MacSweeney et al, 2004; Emmorey et al, 2010), but these methodologies lack the temporal resolution to determine at what stage of processing these differences may occur. The present study is part of a larger series of experiments designed to pit sign recognition against human-action recognition in paradigms that permit testing of both sign-naive participants and skilled signers in a temporally sensitive fashion. In this way, we can ascertain the effects of recognition that arise from the demands of perceptual processing of human forms, in relation to those attributable to specialized linguistic knowledge of sign forms.

Psycholinguists have argued that in spoken languages, word recognition is achieved through the mapping of the acoustic speech signal received by the ear onto stored mental representations of word forms in the listener's mind (though the exact nature of such representations is still a matter of debate). The mapping process unfolds in time as the acoustic signal of the word accrues, and is thought to be mediated by psychological representations which serve in part to rectify variances in the signal due, for example, to coarticulatory factors, allophonic variation, and cross-speaker differences.

Spoken-language recognition is remarkably robust to variations in perceptual form. The term "lack of invariance" is often used to describe this quality of speech perception, through which, despite measurable and often profound deviations in the spectral properties of speech sounds, listeners impose consistent linguistic interpretations (e.g. Liberman, 1957; Liberman et al, 1967; see also Browman & Goldstein, 1986).

Extending this account by analogy, to the extent that signers have comparable mental representations of sign forms, they might show differential sensitivities to (i.e. be less affected by) perceptual deviations during sign recognition compared to naive viewers. We speculated that one property which may differentiate language perception from gesture recognition more generally was the degree to which sign language recognition may be robust to perceptual changes that arise from changes in viewpoint.

In contrast, an additional literature relevant to our experimental manipulations and results derives from more general considerations of the viewpoint invariance problem in object and biological motion recognition (Biederman, 1987, 2000; Marr & Nishihara, 1978; Pavlova & Sokolov, 2000; Tarr, 1995; Tarr & Pinker, 1989, 1990). Particularly relevant to the present studies is how individuals recognize human body poses and actions in the context of varying point-of-view. Daems & Verfaillie (1999), for example, describe a series of priming experiments exploring the relevance of orientation to the recognition of static human poses and implied actions. These data showed evidence of orientation-specific effects on accuracy and in categorization; the authors argued from this that the representations that mediate action and body identification are sharply tuned to a particular perspective (see also Verfaillie, 1993).

To the best of our knowledge, the present study is the first attempt to address which of these two descriptions—"lack of invariance" versus perspective-specific representations—would provide a better account of early perceptual stages of language processing in the visual modality. In addition to informing theories of sign recognition, such results have implications for the design of visually-based assistive technologies such as videophones and teleconferencing, and the increasing use of these technologies in the delivery of interpreting and community services for deaf signers.[1] To investigate the influence of changes in viewpoint on sign and gesture recognition, we examined sign and gesture recognition under conditions of through-plane rotation. Through-plane rotation is often encountered in natural settings, in which a signer may approach a group of signing friends and begin to process signing from an non-canonical perspective (e.g. from the side and not head-on).[2] It is important to note that these stimuli differ in many ways from those in Daems & Verfaillie (1999); most importantly, our stimuli consist of video-clips displaying dynamic upper-torso, arm, hand and facial movements associated with naturalistic signing, rather than static images implying whole-body movements.

2. Methodology

In this experiment subjects were presented with a sequence of short video clips and were asked to make a speeded categorization as to whether each clip showed an ASL sign or a non-linguistic gesture. Within this self-paced continuous categorization task, we manipulated sequential co-occurrences of particular image pairs to examine the effects of repetition priming within each stimulus class (to be referred to subsequently as action-types[3]: signs or gestures) and by viewpoint (Front, Left or Right). In this paradigm, if two adjacent stimuli are the same sign (e.g. DOLL, DOLL[4]) or gesture (e.g. Rub Eye, Rub Eye) they are considered related by content, regardless of the point-of-view of the images displayed. If two sequential stimulus items are filmed from the same camera angle (e.g. HOME-*Front-view*, ISLAND-*Front-view*) they are considered related by point-of-view, and contrasting in content. To establish priming effects, we consider the effects of content and point-of-view in

[1] We thank an anonymous reviewer for calling attention to this applied dimension of our work.
[2] Note that this is only one manipulation in which invariance might be relevant in sign perception; other situations might include, for example, viewing male vs. female or young vs. old signers, characteristic signing behavior on the part of individuals, prosodic variation due to temperament, effects of environmental lighting (e.g. full sunlight vs. shadow), and so on. In addition, we make no claims for how the current manipulation of perceptual viewpoint in signing is related any one of the possible modifications of the speech signal that may also be subject to the phenomenon of perceptual invariance.
[3] Note that we use the term "action-type" instead of "lexicality" because we consider the gestures used in this study to be non-linguistic. So the distinction here is not between existing words and accidental gaps, the latter obeying the phonological rules of the system but happening not to occur in the ASL lexicon. Such gaps in the sign lexicon are called "non-signs" and are mentioned again later, in the general discussion section.
[4] As is customary in the sign language literature, glosses of ASL signs are given in capital letters.

cases where two stimuli are either related or unrelated along these stimulus dimensions. We present the results of five experimental manipulations that are afforded by our experimental design.

In the first analysis (Section 3.1) we validate that repetition priming is occurring in the context of this categorization task. We determine that subjects tend to be faster in categorizing the second of two adjacent within-class stimuli as a sign or a gesture when the two items are related by content (e.g. for DOLL, DOLL vs. TREE, DOLL). The same does not hold for paired items that are related only by viewpoint (e.g. HOME-*Front-view* vs. ISLAND-*Front-view*). As will be discussed below, this analysis allows us to separate out the effects of the repetition of the content of the depicted action-type from the effects of the repetition of viewpoint. This analysis confirms the utility of the experimental design in which repetition priming affects the categorization of the stimuli as signs or gestures. Following this validation we present selective assessments of the magnitude of repetition priming observed.

The second and third analyses (Sections 3.2 and 3.3) are germane to the main question of interest and present analyses in those cases where repetition priming is occurring. In these analyses we assess whether the magnitude of repetition priming observed in cases of related action-types is invariant as a function of viewpoint. For example, we ask if the magnitude of priming that occurs in the stimulus pair (Pull Ear- *Front-view*, Pull Ear-*Front-view*) is statistically equivalent to the magnitude of priming that occurs in the stimulus pair (Pull Ear-*Left-view*, Pull Ear-*Front view*).

In all cases we assess these differences for each class of action-type (i.e. sign or gestures) and for each participant group (deaf or hearing). Recall that the invariance hypothesis predicts that deaf signers will show equivalent priming for sign pairs irrespective of viewpoint, while hearing subjects will not. Whether deaf signers also show invariance for non-linguistic gestures is also explored. Additionally, in Sections 3.4.1 and 3.4.2 we consider the possible relevance of age of acquisition in two similar analyses comparing early and late learners of ASL.

2.1. Subjects

In this task, a total of 76 participants took part, of whom 43 were deaf (25 female) and 33 were hearing (19 female). Thirteen subjects were left-handed. For the purposes of the age of acquisition analysis discussed in Section 3.4, the deaf subjects were split into two subgroups, those exposed to ASL before age 8 ("early"-exposed learners, n=22), and "late"-exposed learners (n=21). The majority of the hearing subjects were undergraduate students at the University of California at Davis, and 25 of the deaf subjects were students at Gallaudet University. The other subjects were residents of northern California who were recruited through advertisements and word-of-mouth. Subjects were given either course credit or a fee for participating. All gave informed consent in accordance with established IRB procedures at UC Davis and Gallaudet University.

2.2 Stimuli

Each subject viewed a sequence of short (mean=1029 ms; range=[701 ms, 1635 ms]) video clips, each showing a person performing an action which could either be an ASL sign or a non-linguistic grooming gesture such as head scratching. The entire sequence consisted of approximately 450 video clips, lasting a total of approximately 13 minutes. The live action shown in each clip was performed by one of two deaf performers, one of whom was male and the other female. Each action was filmed from three viewpoints: straight-ahead Front view ("F"), from the Left ("L"), or from the Right ("R"); this was accomplished through the use of three time-locked video cameras when the actions were originally filmed.[5] Each action was articulated and filmed in isolation, not as part of a longer utterance. Sign and gesture forms were chosen from stimuli which had been filmed using the simultaneous capture set-up. A number of constraints were used to pick the stimuli, which needed to be easily identifiable (having no major occlusions) and balanced overall between the two performers; sign stimuli also had to be mono-morphemic and reasonably common.[6] The non-linguistic grooming gestures included some which were planned in advance of filming and others which occurred spontaneously during the filming session between takes while the cameras were still running (e.g. a performer needing to scratch an itch).

[5] These data were collected as part of a larger study investigating lexical recognition of signs and included additional manipulation of viewpoint and form. The analysis to be presented here is restricted to the F, L and R viewpoints.
[6] We did not explicitly control for sign frequency but note that the Kucera & Francis (1967) written frequency counts of the glosses of the signs (a rough but often-used proxy for sign frequency) were distributed as follows: mean = 207.8, SD = 358.5, range = [6, 1290].

A total of 28 actions (14 signs and 14 gestures, listed in the Appendix, henceforth referred to as *critical actions*) were chosen to appear as targets. The action preceding the target could be a different action or the same action as the target. In the latter case, the target action was in essence a repetition of the prime action, possibly shown from a different viewpoint, but produced by the same performer. Assessments of repetition priming were determined from temporally-adjacent prime-target contexts; that is, the prime was seen, and then in the very next trial, the target was seen. An additional 40 actions (20 signs and 20 gestures) served as "filler" items, and were interspersed among the prime-target clips. Prime-target pairs were separated by a sequence of up to three filler clips. Filler clips could show either gestures or ASL signs and could show those actions from any one of the three viewpoints. In each case, the number of fillers the actions they showed, and their viewpoints were determined randomly.

In analysis presented in Section 3.1, we make use of filler items to serve as unrelated "primes" for purposes of validating the repetition priming procedure. In contrast, the analyses presented in Sections 3.2 through 3.4 based on those instances in which *the same critical action was repeated* and these repetitions constitute the prime and target pairs, but *the viewpoint from which the critical action was shown (Front, Left or Right) could differ between the prime and target clips.*

Shown in Figure 1 is a representative portion of a stimulus sequence illustrating the conditions of interest. In this example, items 1-2, 4-5, 9-10, and 13-14 represent sign or gesture critical-action prime-target pairs. Items 4-5 represent a sequence of two clips showing the sign "M," presented both times in the Front view (hence subscript S (sign), superscript F (Front). Item 4 serves as the prime for the target item 5 in this related pair. Items 13-14 form a prime-target pair showing the same critical action, "M." However, in this pair the prime (item 13) shows the sign from a different point-of-view (Left) from the target (Right); therefore this is a pair that is unrelated in terms of viewpoint. Note that in both pairs 4-5 and 13-14 the target sign is presented from the Front point-of-view. Our second analysis, presented in Section 3.2, explores the priming effects in these types of pairings—identical content, Front-, Left- and Right-view *primes*, Front-view *targets*—to examine the effects of *prime point-of-view* on repetition priming. Items 9-10 represent a pair of clips showing the gesture "H" in which the target, shown from the Right view, has a Front-view prime. This condition can be contrasted with that of pair 1-2 to examine effects of *target point-of-view* on repetition priming. Our third analysis, in Section 3.3, examines these cases of Front-, Left- and Right-view *targets* preceded by Front-view *primes*. Finally items 3, 6, 7, 8, 11 and 12 are considered "fillers"; however for our preliminary analysis in Section 3.1, we will consider filler stimuli like item 8 to serve as "primes" for immediately-following critical-action items like item 9. Thus, items 8-9 represent an unrelated prime-target condition that may be can be contrasted to item sequence 1, 2 (a related prime-target condition) to examine the effects of related and unrelated *content*.

$$[1H_G^F\ \ 2H_G^F]\ \ 3A_G^L\ \ [4M_S^F\ \ 5M_S^F]\ \ 6O_S^R\ \ 7K_G^L\ \ 8P_G^F\ \ [9H_H^F\ \ 10H_G^R]\ \ 11B_S^F\ \ 12C_G^R\ \ [13M_S^L\ \ 14M_S^F]\ \ldots$$

Figure 1. Example sequence of 14 stimuli within the experiment. The superscripts indicate: F = Front view, L = Left view, R = Right view. The pairs of items in square brackets are critical-action prime-target pairs. The subscript indicates whether the item is a gesture (G) or sign (S). The content (action shown) in each item, represented by the letter next to the sequencing number, is the same within square-bracketed pairs but in general varies elsewhere.

Over the course of the task, each critical action (whether a sign or gesture) was presented in a prime-target pair a total of four times (i.e. eight occurrences total: four times as a prime and four times as a target). For each subject, randomization was performed on the entire set of prime-target pairs, so that different subjects saw the same critical actions, but in a different order. The viewpoints from which a given critical action was seen in its occurrences in target-prime pairs also varied from subject to subject. Assignment of viewpoints to critical action pairs was made pseudo-randomly with the following proviso. As three views (Front, Left and Right) of each critical action were available and four prime-target pairs for each critical action were to be viewed over the course of the experiment, theoretically 3^8 (=6561) distinct sequencings of each critical action would be possible. Because only some of these would be considered useful for our analysis, the viewpoint sequences within prime-target items were limited to a relatively restricted subset. Our main focus here will be on prime-target pairs in which either the prime or the target was seen in the canonical "Front" view.[7]

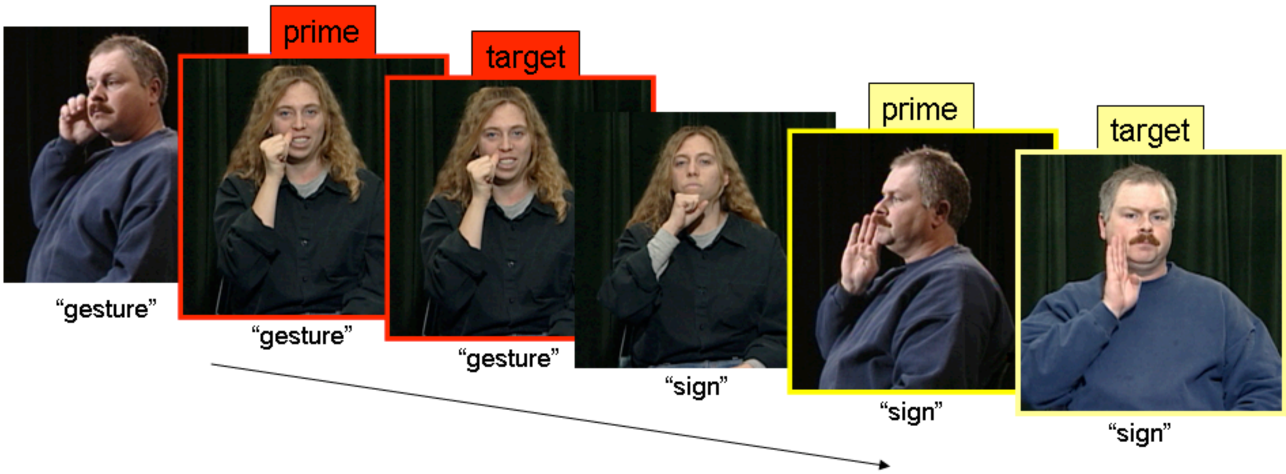

Figure 2. Typical sequence of video stimuli, illustrating same-content prime-target pairs. Starting at the left: a filler gesture item (Left view), followed by a prime-target gesture pair (in red, Front view followed by Front view), a filler sign item (Front view), and a prime-target sign pair (in yellow, Left view followed by Front view). The word in quotation marks under each item corresponds to the correct categorization of the stimulus.

2.3. Task

The subject was told that he/she would be watching a series of short video clips and that the task was to decide as quickly as possible whether each clip showed an ASL sign or a non-linguistic gesture and to categorize the stimulus accordingly. Responses were registered by pushing one of two buttons. The task was balanced for response hand (i.e., whether the left- or right-handed button was used to respond to signs) and for handedness of participant. A head-chin mount (UHCO HeadSpot, Houston, TX) was used to maintain a consistent 24-inch distance from the subject's eyes to the computer screen. The task was administered and data collected using Presentation software (Neurobehavioral Systems, Albany CA).

Before the experiment began, each subject was given a short training exercise, identical in format to the actual experiment, during which the subject viewed and categorized 30 video clips. The signs and gestures in

[7] Thus, the prime-target pair orderings to be examined in this paper are: FF, LF, RF, FL and FR. While this permits us to consider the effects of stimulation rotation in relation to the canonical Front view, we note that this design also means that each action was seen from the Front view more often than in other orientations.

the training clips were different from those shown during the actual experiment and feedback for correctness was given during the training task. Subjects were told after the warm-up task that the experiment would not provide feedback for correctness, only for appropriately-timed responses (not too fast or slow, discussed below). Hearing subjects, who had no formal knowledge of ASL, were instructed to simply make their best judgment and respond as quickly as possible even if they were uncertain. Figure 2 shows screen captures of representative video clips as they appeared during the experiment, along with the expected answers to each item. The grooming gestures tended not to resemble signs when seen in their entirety (as opposed to the still shots in Figure 2), and as seen in the accuracy data, hearing subjects were generally quite successful in making these categorizations.

Feedback for correctness was not given to subjects during the actual experiment. However, in order to encourage them to respond quickly, two rapidly-shortening horizontal green lines were displayed during each trial, one above and one below the video clip being presented, indicating the amount of time remaining for the subject to respond. In addition, a brief (approx. 300 ms) message screen reading “TOO SLOW” was shown after a trial if the response for that trial came more than 400 ms after the end of that video clip. Similarly, to prevent subjects from speeding through the experiment without sufficient attention to the task, a similar message screen reading “TOO FAST” was given if response time for a given trial was under 300 ms. Responses outside the RT windows just described were deemed “invalid;” if such a response was given during the presentation of a prime-target pair, or if no response at all was given, that pair was repeated later. Overall, the incidence of such “invalid” trials was about 1%. After each “valid” trial, a brief (approx. 300 ms) screen with a small green square was presented, indicating to the subject that they had responded within the appropriate time window for that trial and that the next trial was forthcoming.[8] The interval between trials (from end of feedback screen to start of next video) was 218 ms. Therefore, the total ISI (end of one video to start of next video)—whether between filler, prime or target items—was always about 500 ms.

[8] In addition to helping keep subjects on-task, an additional aim of these windowing techniques was to provide more homogeneity in response times across subject populations; an analysis of within-group distributions, to be presented later, indicates that this goal was achieved.

2.4. Data analysis

Accuracy and RT for categorizing target video clips, along with the associated priming values, served as dependant measures. The analyses for accuracy were performed after performing an arcsine transformation (y=arcsin(sqrt(x)) on the initially-obtained percentage data, but for clarity of presentation the summary information given for accuracy has been back-transformed into percentage scores (Wheater & Cook, 2000). Reaction time and priming analyses were performed on correct responses only.

Response times were considered to be outliers if they were more than 3 SDs away from the mean among the results for a given subject (over all actions of that action-type, i.e. sign or gesture) or a given action (over all subjects of the same group, i.e. deaf or hearing). Outliers were replaced with the average of two quantities—the subject's average RT for that action-type, and the average RT over all subjects of the same group (deaf or hearing) associated with that critical action. Overall, the proportion of RT values classified as outliers and so replaced was 0.95%. Moreover, data for both members of a video clip pair were rejected if the subject did not respond to both the prime and target correctly, or did not make each response within the requisite time window.[9] In rare cases, this conservative procedure resulted in a subject not having any valid data points for a specific condition of interest; in these cases a group mean for that condition was used to fill in the missing value.[10]

2.5. Overview of results section

In Section 3.1 we conduct a priming analysis in which we compare subjects' RT and accuracy for target action-clips that were preceded by a related or unrelated prime.

The results of this initial analysis indicate that overall, (1) priming effects are present for both signers and non-signers, and (2) priming occurs in a given trial in the event that the same action was seen in the preceding trial, but does *not* occur when the current and preceding trial showed different actions from the same viewpoint. In

[9] Recall that in this self-paced continuous categorization task, subjects responded to each stimulus.
[10] This occurred for 3.73% of the reaction time data, 3.27% of the priming data, and 1.64% of the accuracy data. Analysis with the values omitted, versus replaced, did not substantially change the reported effects.

other words, it is the repetition of a particular *action* that governs priming, not the repetition of a particular *viewpoint*. This result establishes the viability of this repetition priming paradigm in which categorization is required and that the viewing conditions (viewpoints) are not themselves a source of priming effects. Having established in our initial analysis that priming occurs, in Sections 3.2 and 3.3 we explore the more nuanced question of how the viewpoint in which actions are seen might influence such priming effects, and whether this differs between subject groups or action-types.

In Sections 3.2 and 3.3 we restrict the analysis to prime-target pairs in which the content of the prime and target are the same (i.e. those cases in which repetition priming is occurring). In Section 3.2 we examine cases where the prime varies as a function of point-of-view (Front, Left, Right) and the target is a Front-facing image. Conversely, in Section 3.3 we examine pairs where the prime is Front-facing and the targets vary in point-of-view. We examine magnitude of priming as well as accuracy in these cases.

The clearest support for a sign-specific "invariance of perception" phenomenon in our analyses would be a persistent three-way interaction of Group, Action-type and Viewpoint, with deaf signers showing similar results across viewing conditions (Front, Left or Right) for sign stimuli in particular. Additionally, we would expect hearing non-signers to show modulations of our dependent variables as a function of Viewpoint. On the other hand, consistent main effects of Viewpoint without such three-way interactions would be more in line with previous work like that of Daems and Verfaillie (1999), discussed earlier. Our results show that both groups pattern similarly with respect to action-type and viewpoint. These results do not support an "invariance of perception" interpretation of the data.

Finally, in Sections 3.4.1 and 3.4.2, we explore the possible relevance of age of acquisition by performing two separate analyses of the deaf group. Here, we compare two subgroups—early and late acquirers of ASL. Yet again, as was the case with the comparison of the hearing and deaf groups, no substantial differences are found in the overall patterning of the results with respect to action-type and viewpoint. This finding is consistent with the previous results in which little evidence of "invariance of perception" has been found in this sign-gesture categorization task.

In each of these analyses, we use ANOVA to investigate the relevant dependent variables (RT and accuracy for the initial analysis, priming and accuracy for the later analyses). In each case we report the outcomes of both subjects (F1) and items (F2) analyses, using the Huynh-Feldt correction when appropriate and following up with planned and post-hoc comparisons when such results are germane to the discussion.

3. Results

3.1. Initial RT analysis: Evaluation of viewpoint and stimulus identity

In principle, the effects of repetition on categorization of successive stimuli may be affected by two independent factors: (a) the actions shown in the stimuli and (b) the viewpoints from which actions are shown. We performed four-way ANOVAs with factors of Group (deaf vs. hearing), Action-type (sign vs. gesture), Viewpoint (Front, Left, or Right), and Relatedness of content (same action in prime and target, vs. different action) to evaluate reaction time and accuracy in the categorization of stimuli across conditions.

3.1. Initial RT analysis: Evaluation of viewpoint and stimulus identity

Front-view targets	RT in ms (unrelated condition)				RT in ms (related condition)				Accuracy			
	Viewpoint of prime				Viewpoint of prime				Viewpoint of prime			
Deaf	F	L	R	All views	F	L	R	All views	F	L	R	All views
Signs	678	688	678	681	521	553	578	551	97.6%	98.1%	99.0%	98.3%
Gestures	746	730	723	733	520	556	552	543	96.3%	94.9%	97.1%	96.2%
Overall	712	709	700	707	521	554	565	547	97.0%	96.7%	98.2%	97.3%
Hearing												
Signs	833	821	809	821	615	664	672	650	88.3%	93.8%	93.9%	92.2%
Gestures	856	840	831	842	577	630	637	615	95.0%	94.5%	92.9%	94.2%
Overall	844	830	820	832	596	647	655	633	91.9%	94.2%	93.4%	93.2%

Table 1. Overview of reaction-time and accuracy means for the deaf and hearing groups.

The reaction-time analysis revealed main effects of Group ($F1(1,74)=30.4$, $MSE=81518$, $p<0.001$; $F2(1,26)=260.1$, $MSE=3780$, $p<0.001$), Relatedness ($F1(1,74)=476.4$, $MSE=15209$, $p<0.001$; $F2(1,26)=635.7$, $MSE=4231$, $p<0.001$), and an effect of Viewpoint that was significant by subjects only ($F1(2,148)=4.55$, $MSE=6148$, $p<0.05$); $F2(2,52)=2.12$, $MSE=4956$, $p=0.13$). Also seen were two-way interactions of Action-type by Group ($F1(1,74)=5.69$, $MSE=8253$, $p<0.05$; $F2(1,26)=5.07$, $MSE=3780$, $p<0.05$), Relatedness by Viewpoint ($F1(2,148)=15.8$, $MSE=6113$, $p<0.001$; $F2(2,52)=6.11$, $MSE=4243$, $p<0.01$), Action-type by Relatedness ($F1(1,74)=26.2$, $MSE=7273$, $p<0.001$; $F2(1,26)=28.5$, $MSE=4231$, $p<0.001$) and Relatedness by Group ($F1(1,74)=5.42$, $MSE=15209$, $p<0.05$; $F2(1,26)=11.3$, $MSE=4665$, $p<0.01$). No other interactions were significant ($F\text{'s}<1.5$).

Table 1 provides an overview of the mean results for the two groups in our conditions of interest. The main effect of Group reflects the fact that overall, deaf subjects were faster at categorizing the stimuli than hearing non-signers (627 ms vs. 732 ms). The main effect of Relatedness shows, as expected, that the ability to categorize a stimulus item was faster if it had been preceded by a stimulus item that was identical in content (590 ms vs. 769 ms). The effect of Viewpoint is due to Front-view stimuli being associated with faster RTs overall than Left- or Right-view stimuli (668, 685 and 685 ms respectively, $p\text{'s}<0.01$ for the Front vs. Left and Front vs. Right comparisons).

The two-way Relatedness by Viewpoint interaction (see Figure 3) shows that in general, the Viewpoint of the preceding video clip only modulated categorization in the case of a “related” stimulus (i.e. in the case of identical stimulus actions in the current and preceding clip); in such cases, responses when the preceding clip was Front-view were faster than when the preceding clip was Left- or Right-view ($p<0.001$), with the difference between the latter two conditions being non-significant (respective RTs = 558, 601, 610). Respective RTs in the unrelated condition were 778, 770 and 760 ms, with all differences non-significant. This is an important finding as it indicates that there is little to no effect of the Viewpoint modulation independent of the stimulus content. This result shows that categorizations are modulated by repetition effects of stimulus content.

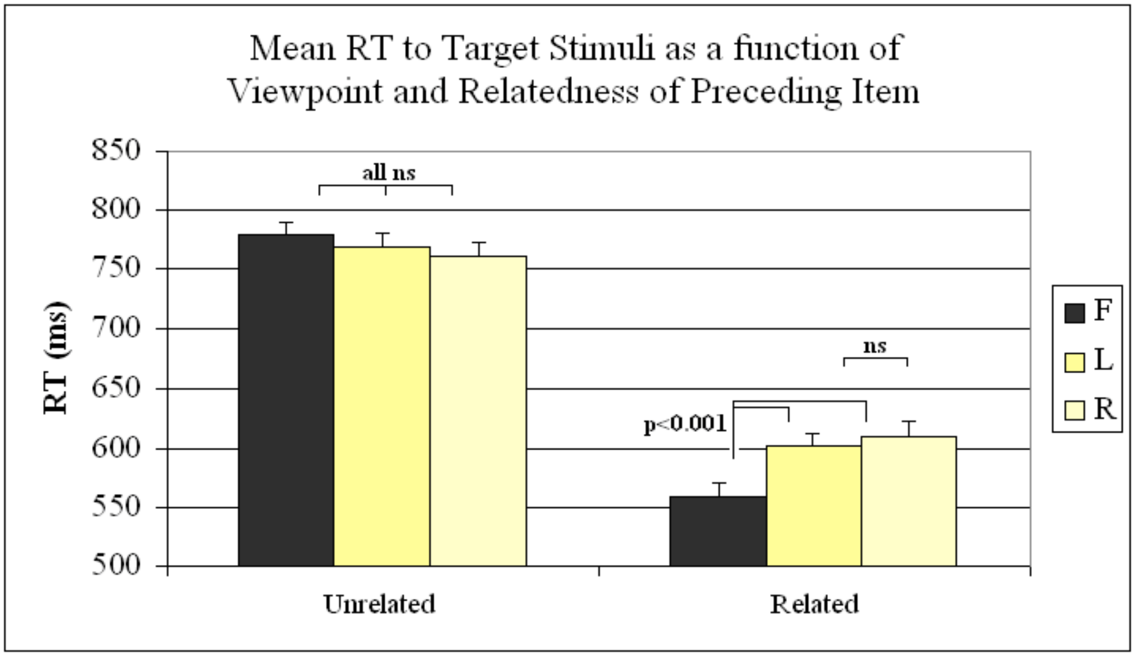

Figure 3. Average reaction times to categorize a stimulus, as a function of preceding-stimulus Viewpoint and Relatedness; F=Front, L=Left, R=Right.

The two-way Action-type by Relatedness interaction indicated that overall, the categorization of signs with related primes was slower than that of signs with unrelated primes (751 ms for unrelated signs vs. 600 ms for related signs, $p<0.001$). Similarly, unrelated gestures with unrelated primes were slower to categorize than gestures preceded by related primes (788 vs. 579 ms, $p<0.001$). However as shown in Figure 4, the magnitude of the saving was overall greater for gestures compared to signs. The differences in magnitude of priming may be related to the fact that sign stimuli were on average slightly shorter in duration than gestures (984 ms for signs vs. 1094 ms for gestures); this difference in stimulus length was not, however, statistically significant. The interaction of Group with Relatedness is due to the fact that hearing subjects showed somewhat more time savings in the related prime-target conditions than deaf subjects did (707 vs. 547 ms for deaf, 832 vs. 633 ms for hearing, p's<0.001)

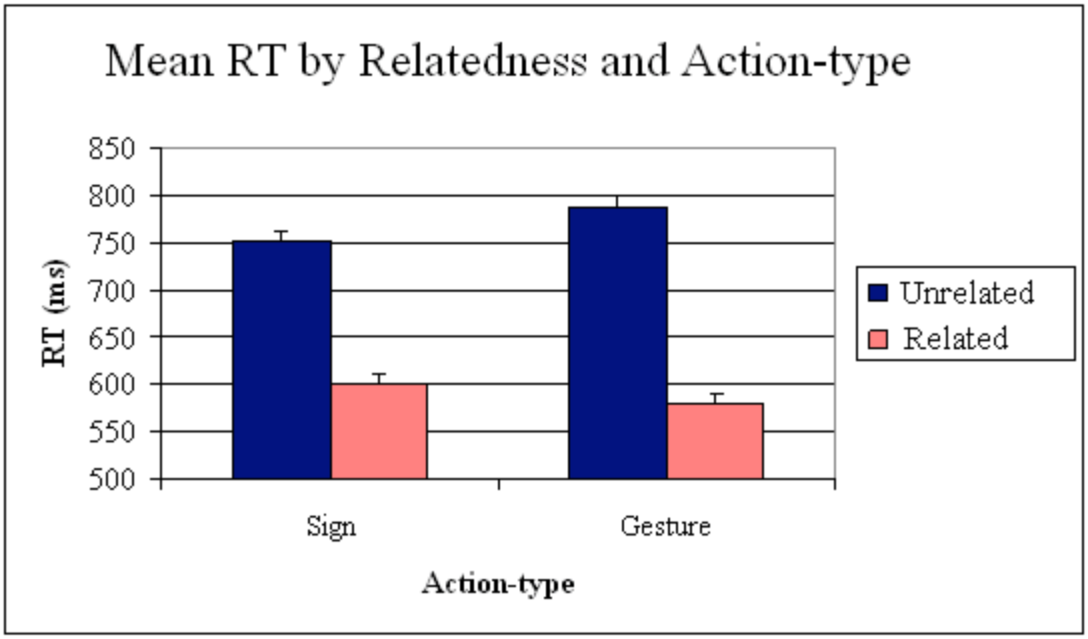

Figure 4. Average reaction times to categorize a stimulus, as a function of Action-type and Relatedness. Note all four comparisons (sign versus gesture, related versus unrelated) are significant at least the $p<0.01$ level.

The two-way Action-type by Group interaction shown in Figure 5 is due to the fact that deaf subjects were faster at categorizing signs relative to gestures (616 vs. 638 ms, $p<0.01$) while hearing subjects showed a non-significant trend in the opposite direction (736 ms for signs vs. 728 ms for gestures, $p=0.43$). The group difference was highly significant for both signs and gestures (both p's<0.001).

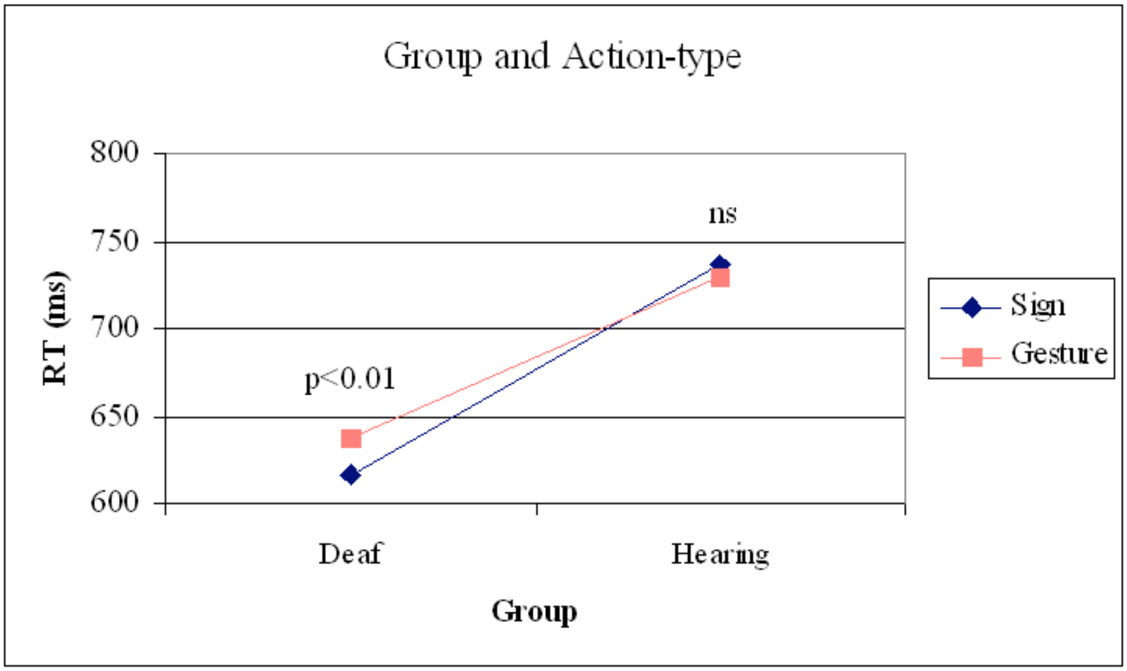

Figure 5. Average reaction times to categorize a stimulus, as a function of subject Group and stimulus Action-type.

An analysis of the accuracy data showed main effects of Group (F1(1,74)=8.51, MSE=0.262, $p<0.01$; F2(1,26)=25.3, MSE=0.026, $p<0.001$) and Relatedness (F1(1,74)=126.7, MSE=0.051, $p<0.001$; F2(1,26)=97.3, MSE=0.029, $p<0.001$). Also seen were a two-way interaction of Action-type by Group (F1(1,74)=4.86, MSE=0.129, $p<0.05$; F2 (1,26)=11.8, MSE=0.026, $p<0.01$), and two other interactions that were significant by subjects only: Viewpoint by Action-type (F1(2,148)=4.04, MSE=0.045, $p<0.05$; F2<2) and Action-type by Relatedness (F1(1,74)=5.90, MSE=0.038, $p<0.05$; F2<2).

The main effect of Group shows that in general deaf subjects were more accurate than hearing subjects (97.3% vs. 93.2%). This effect however must be qualified in light of the two-way Action-type by Group interaction which shows that while deaf signers showed high levels of accuracy in categorizing signs and gestures, exhibiting higher accuracy for the former (98.3% for signs vs. 96.2% for gestures, $p<0.05$), hearing subjects trended in the opposite direction (92.2% for signs vs. 94.2% for gestures, $p=0.27$). Note that these trends follow the patterns of RT discussed above. Post-hoc comparisons indicated that deaf and hearing subjects differed in the accuracy of the categorization of signs (deaf 98.3% vs. hearing 92.2%, $p<0.001$), but did not differ in the categorization of gestures (deaf 96.2% vs. hearing 94.2%, ns). The main effect of Relatedness showed that categorization of target stimuli preceded by related primes was more accurate than of target stimuli preceded by unrelated primes (related 98.4% vs. unrelated 91.3%, $p<0.001$).

3.1.1. Discussion

The results for reaction time and accuracy are highly complementary, and several findings emerge from this preliminary analysis. Importantly, the effects of Relatedness make it clear that the relationship between prime and target (i.e. stimulus repetition) modulates categorization accuracy and reaction times. Specifically when prime and target constitute a related stimulus, reaction times to categorize the target are faster than when the prime is unrelated to the target. Moreover within the related conditions the fact that identical content and viewpoint lead to the reaction times that are significantly faster than identical content that differs in view point is compatible with the findings of Daems and Verfaillie (1999). This finding demonstrates that our paradigm is useful in establishing repetition priming effects in the context of a sign/gesture categorization task. The data also indicate that Viewpoint variation *alone* has little effect. That is, having seen Stimulus A viewed from a Front (or side) perspective does little to modulate the categorization of Stimulus B that shares the same viewpoint, when the two stimulus items show different actions. In addition the data make clear that deaf subjects overall performed faster and more accurately than hearing subjects. Moreover, we observe that deaf signers were faster and more accurate in categorizing signs than gestures, while hearing subjects tended to show the opposite pattern—that is, hearing subjects tended to be faster and more accurate at categorizing gestures compared to signs. The overall accuracy advantage shown by deaf subjects over hearing subjects was seen mostly in the sign data ($p<0.001$), as the two groups were about equally accurate in categorizing non-linguistic gestures. Finally, for both groups the overall magnitude of priming was greater for gestures than signs, which may reflect the small difference in the length of our stimulus classes.[11]

[11] To investigate further the possibility of within-group variability that might differ between the hearing and deaf groups, we carried out a further analysis of the distributions of priming values within each group. Other than the difference, discussed earlier, by which the hearing group showed greater priming than the deaf group, there was also greater overall variance within the hearing group (for priming over all contexts, SD = 79.3 ms for the hearing group vs. 46.5 ms for the deaf group, $p<0.01$ by Levene test). However, neither group departed significantly from zero in terms of skewness (0.019 for deaf, SE=0.361; -0.254 for hearing, SE=0.409) or

We now turn to a more direct assessment of effects of perceptual variation in our data. Specifically we assess the degree of repetition priming under conditions in which identical actions are compared but viewpoint is varied.

3.2. Priming analysis: Front-view targets preceded by Front-, Left- or Right-view primes

To directly assess whether changes in viewpoint affect deaf signers' and hearing non-signers' categorization of signs and gestures equivalently, we examined magnitude of priming (prime RT minus target RT) and accuracy using three-way ANOVAs by subjects (F1) and items (F2) with factors Group (deaf vs. hearing), Action-type (sign vs. gesture) and Viewpoint of prime (Front, Left, Right). Note in this and all following analyses the content of the stimuli are the same, but the viewpoint of the prime varies.

Along the lines discussed earlier, to the extent that perceptual invariance comes into play in this categorization task, we might expect the amount of repetition priming observed during the categorization task to be equivalent for deaf subjects regardless of the viewpoint of the prime, while for hearing subjects, perceptual differences due to changes in viewpoint may modulate categorization. A further question of interest is whether any such effects may vary as a function of Action-type (i.e. for signs vs. gestures). Specifically, to the extent that group differences are observed, will deaf subjects' effects be restricted to sign language stimuli? On the other hand, analogous repetition priming effects across Viewpoints, in the absence of interactions with Group and Action-type, could be taken as support of previous findings that the representations that mediate actions are tuned to particular perspectives.

3.2.1 Results

Front-view targets	Priming (ms)	Accuracy

kurtosis (-0.945 for deaf, SE=0.709; -0.330 for hearing, SE=0.798). This general pattern held true for the entire dataset as well as for each action-type and stimulus viewpoint.

	Viewpoint of prime				Viewpoint of prime			
Deaf	F	L	R	All views	F	L	R	All views
Signs	172	140	149	154	99.3%	99.6%	99.7%	99.6%
Gestures	206	219	189	205	99.3%	98.2%	99.9%	99.3%
Overall	189	180	169	179	99.3%	99.0%	99.8%	99.4%
Hearing								
Signs	219	198	159	192	92.4%	97.2%	96.4%	95.5%
Gestures	267	246	243	252	97.3%	98.9%	96.9%	97.8%
Overall	243	222	201	222	95.2%	98.1%	96.6%	96.8%

Table 2. Overview of priming and accuracy means for the deaf and hearing groups for critical-action pairs with Front-view targets preceded by Front-, Left- or Right-view primes.

The priming analysis revealed main effects of Group (F1(1,74)=6.92, MSE=29668, $p<0.05$; F2(1,26)=22.9, MSE=4275, $p<0.001$), Viewpoint (F1(2,148)=6.56, MSE=4303, $p<0.01$; F2(1.43,37.3)=3.83, MSE=9414, $p<0.05$) and Action-type (F1(1,74)=34.7, MSE=9944, $p<0.001$; F2(1,26)=25.4, MSE=5746, $p<0.001$). No interactions were significant (F's<2).

The accuracy data confirm the finding of the initial analysis that for the most part, subjects in both groups were able to perform the categorization task correctly. However, a main effect of Group was observed (F1(1,74)=7.12, MSE=0.174, $p<0.01$; F2(1,26)=16.3, MSE=0.023, $p<0.001$). There was also a Group by Action-type interaction that was significant by items but only marginally significant by subjects (F1(1,74)=3.17, MSE=0.059, $p=0.08$; F2(1,26)=4.56, MSE=0.023, $p<0.05$). A marginally significant Group-by-View interaction was observed by subjects ($p<0.054$) but failed to reach significance by items. No other effects or interactions reached significance.

An overview of the mean results for both groups is presented in Table 2. The Group effects are due to the fact that deaf subjects showed less priming than hearing subjects (179 vs. 222 ms) and were more accurate than hearing subjects (99.4% vs. 96.8%) The effect of Action-type was due to signs producing less priming overall than gestures (173 vs. 228 ms); however responses to sign and gestures were not significantly different in terms of accuracy. The effect of prime Viewpoint showed that categorization for Front-Front stimulus pairs led to the greatest saving for categorization, followed by Left-Front, with Right-Front pairs showing the least amount of savings (Front-Front 216 ms, Left-Front 201 ms, Right-Front 185 ms). The priming difference for F-F vs. R-F was significant ($p<0.01$); the difference for F-F vs. L-F was marginally significant ($p=0.07$).

The interaction of Group by Action-type in the accuracy results is due to the fact that deaf subjects' categorization of sign and gestures were similarly accurate (signs 99.6% vs. gestures 99.3%), while hearing subjects were somewhat less accurate responding to signs than to gestures (95.5% vs. 97.8%, $p=0.07$). The marginally significant Group-by-View interaction for accuracy found only in the subjects analysis was due to the fact that hearing subjects tended to have better accuracy in the Left prime condition than in the Front prime condition (95.2% vs. 98.1%, $p<0.01$), while deaf subjects showed equivalent accuracy across viewing conditions. No other significant viewpoint-based differences within either group were observed.

3.2.2. Discussion

The priming results indicate that hearing subjects benefitted somewhat more from the repetition of items; overall data for both groups showed that Front-view primes afforded the greatest time savings, and that each group was affected by the through-plane rotations.[12] These data provide some evidence for group differences by which deaf signers were more accurate than hearing subjects in categorization of the stimuli and further, that categorizations were modulated by action-type. Perhaps more surprising, however, is the fact that the data provide little evidence of deaf and hearing subjects being differentially affected by the effect of prior

[12] One may wonder if the inherent difference in RT between deaf and hearing subjects for categorization may have somewhat limited our abilities to detect group-level differences in priming, so we performed an additional analysis for which we transformed the raw priming scores by expressing them as percentage of priming observed relative to the RT for the prime. Analysis of these normalized data permits us to explore whether the percentage of priming observed for each group differed systematically. To assess whether perceptual variance affected deaf signers' categorization of signs and gestures equivalently to that of hearing non-signers, we examined normalized magnitude of priming in prime-target pairs with Front-view target items, using a 3-way ANOVA with factors Group (deaf vs. hearing), Action-type (sign vs. gesture), Viewpoint of prime (Front, Left, Right). These results were highly similar to those for non-normalized priming data discussed above: we observed main effects of Group (significant only by items), Action-type and Viewpoint. The main effect of Action-type indicated that overall, signs led to less priming than gestures (19.7% vs. 26.4%, $p<0.001$). The main effect of Viewpoint reflected perspective-related differences in normalized priming (by Viewpoint of prime: Front 25.3%, Left 22.1% and Right 21.8%; the Front vs. Left and Front vs. Right differences were significantly different, p's<0.01). These complement the findings reported above that overall, through-plane rotation does not differentially affect deaf and hearing individuals in the performance of the categorization task.

exposure to an identical stimulus in the context of through-plane rotation. Most importantly, we note the absence of a three-way interaction that would suggest the presence of an invariance phenomenon.

That both deaf and hearing subjects appeared to benefit from the perceptual prime conditions equivalently (showing an apparently similar degree of influence associated with various viewing conditions) suggests that perceptual invariance is not differentially observed across groups, nor by Action-type (sign vs. gestures). However, one methodological factor that may have influenced these data is the fact that subjects in this protocol had more opportunities to categorize actions viewed in Front-Front pairs than in other viewpoint pairs. Accordingly, somewhat smaller standard deviations were associated with Front-Front pairs relative to Left-Front and Right-Front pairs, perhaps undermining our expectations that the non-canonical viewpoint primes should show equivalent priming for the deaf signers as Front-view primes. Therefore, a more informative assessment in seeking to determine whether perceptual invariance is present might be one restricted to Left-Front and Right-Front prime-target pairs. However, with the analysis restricted to Left-Front and Right-Front pairs, no evidence was found for a sign-specific perceptual invariance phenomenon. A related possibility is that the categorization of the canonical Front-view targets was perhaps too easy (cf. Daems & Verfaillie, 1999) and thus our ability to detect differential priming effects was attenuated.

3.3. Priming analysis: Front-, Left- and Right-view targets preceded by Front-view primes

To address whether ease of categorization of Front targets may have attenuated group differences, we examined the data under conditions where as before, subjects were required to categorize each stimulus item as either a sign or a gesture. However in this case the targets themselves varied in through-plane orientation (being either Front-, Left- or Right-facing). In this case we examine the degree of priming provided by the prior occurrence of a canonical Front-view stimulus item. Thus to the extent that a prior categorization of the Front-facing stimulus as either a sign or gesture enables a subsequent categorization of that same stimulus item under conditions of perceptual change, we might expect to observe relatively equivalent effects of repetition priming.

Although we must use caution in directly comparing differences across targets (which, as a function of through-plane rotation, are physically different), comparisons of group differences can be informative.

We analyzed the data using three-way ANOVAs by subjects (F1) and items (F2) with factors Group (deaf vs. hearing), Action-type (sign vs. gesture) and Viewpoint of target (Front, Left, Right) to establish significant patterns in these data. Note that in contrast to the analysis above, here we examine the priming that resulted from having viewed a Front-view prime that was identical in content to the target (which was conditionally varied through-plane).

3.3.1. Results

Variable-view targets	Priming (ms)				Accuracy			
	Viewpoint of target				Viewpoint of target			
Deaf	F	L	R	All views	F	L	R	All views
Signs	172	106	125	134	99.3%	99.9%	99.7%	99.7%
Gestures	206	123	176	168	99.3%	99.7%	99.9%	99.6%
Overall	189	114	150	151	99.3%	99.8%	99.8%	99.7%
Hearing								
Signs	219	122	169	170	92.4%	97.5%	94.9%	95.2%
Gestures	267	199	255	240	97.3%	96.9%	98.0%	97.4%
Overall	243	161	212	205	95.2%	97.2%	96.6%	96.4%

Table 3. Overview of priming and accuracy means for the deaf and hearing groups for critical-action pairs in which Front-, Left- and Right-view targets were preceded by Front-view primes.

The results for priming were significant main effects of Group ($F1(1,74)=14.9$, $MSE=21801$, $p<0.001$; $F2(1,26)=26.7$, $MSE=3119$, $p<0.001$), Action-type ($F1(1,74)=37.9$, $MSE=8034$, $p<0.001$; $F2(1,26)=13.1$, $MSE=6514$, $p<0.01$), and target Viewpoint ($F1(1.69, 124.8)=29.0$, $MSE=9475$, $p<0.001$; $F2(1.65,42.8)=21.4$, $MSE=4070$, $p<0.001$). A Group by Action-type interaction was significant only in the subjects analysis ($F1(1,74)=4.56$, $MSE=8034$, $p<0.05$; $F2<1.5$).

The accuracy analysis yielded a significant effect of Group ($F1(1,74)= 12.6$, $MSE=0.158$, $p<0.001$; $F2(1,26)=18.1$, $MSE=0.049$, $p<0.001$), and an effect of target Viewpoint that was significant by items but not by subjects ($F1(1.75,129.7)=2.20$, $MSE=0.046$, $p=0.12$; $F2(2,52)=4.13$, $MSE=0.026$, $p<0.05$). No other main effects or interactions approached significance.

Table 3 gives an overview of the mean outcomes for the two groups. The priming and accuracy results show that deaf subjects showed less priming than hearing subjects (151 vs. 205 ms) but tended to be more accurate (99.7% vs. 96.4%). The effect of Action-type reflected that overall, signs led to less priming than gestures (152 vs. 204 ms). The main effect of target Viewpoint in the priming analysis indicated a gradation in the magnitude of priming, with the most priming associated with identical Front-Front pairs (216 ms) followed by Front-Right pairs (181 ms), and with Front-Left pairs leading to the least amount of priming (138 ms). Post-hoc analysis indicated that each of these differences was significantly different (p's<0.001). The effect of Viewpoint that was significant by items but not subjects in the accuracy analysis is due to the fact that subjects performed the task somewhat less successfully on Front-view (97.7%) than on Left- or Right-view target trials (98.8% and 98.7%, respectively; $p<0.05$ for the comparison of Front to Left, $p=0.09$ for the comparison of Front to Right).

The lack of interaction for Group and Viewpoint indicated that these effects were uniform and did not differ as a function of sign experience. The trend toward a Group by Action-type interaction indicated that signs were subject to less repetition priming than gestures, with this difference being more pronounced for hearing subjects (deaf: signs 134 vs. gestures 168 ms, $p<0.01$; hearing: signs 170 vs. gestures 240 ms, $p<0.001$).

3.3.2. Discussion

As noted before, we must be cautious in interpreting the results of this analysis, since the target stimuli themselves were varying in viewpoint and hence were physically different. Nonetheless, one can reasonably expect that if an invariance phenomenon were at work here, it would manifest itself as a difference in outcomes between the deaf and hearing groups relative to these viewpoint manipulations, and with respect to sign targets in particular. However, no interaction evidencing such a difference was found. These findings show that all subjects—whether deaf or hearing or whether required to categorize signs or gestures—still showed similar patterns of priming in the context of this more challenging categorization judgment.

3.4. Age of acquisition analysis

Previous research has shown that age of sign acquisition is linked to processing differences in the recognition of signs (Mayberry & Eichen, 1991; Mayberry & Fischer, 1989; Mayberry & Witcher, 2006; Emmorey & Corina, 1990, Corina & Hildebrandt, 2002). In the present study the deaf signers, while all fluent in ASL, also differed in their initial age of exposure. This heterogeneity in our deaf subject population may have led to variance which masked the effects of interest. To address this possibility, we conducted a further analysis restricted to the deaf signers only, whom we divided into two groups: early-exposed to ASL (n=22) vs. late-exposed (n=21), the latter meaning after early elementary school, with a cutoff of age eight.[13]

3.4.1. Front-view targets preceded by Front-, Left- or Right-view primes

Front-view targets	Priming (ms)				Accuracy			
	Viewpoint of prime				Viewpoint of prime			
Early	F	L	R	All views	F	L	R	All views
Signs	172	171	140	161	97.1%	99.5%	99.9%	99.2%
Gestures	207	206	200	204	99.3%	99.5%	99.8%	99.6%
Overall	190	188	170	183	98.4%	99.5%	99.9%	99.4%
Late								
Signs	172	106	158	145	97.3%	99.3%	99.9%	99.2%
Gestures	206	234	177	206	96.8%	95.2%	99.3%	97.4%
Overall	189	170	167	175	97.0%	97.7%	99.7%	98.4%

[13] Thirteen of the 22 early learners were native signers (i.e. learned ASL from infancy from deaf parents). An analysis with three subgroups (Native, Early non-native, Late non-native) did not result in substantially different outcomes and so for the sake of brevity that analysis is not reported.

Table 4. Overview of priming and accuracy means for the early and late learners of ASL, for Front-view targets preceded by Front-, Left- or Right-view primes.

To examine repetition priming effects as a function of prime viewpoint in the categorization of Front-facing targets, we conducted three-way ANOVAs with factors of Group (early learners vs. late learners), prime Viewpoint (Front, Left or Right) and Action-type (sign vs. gesture). The priming analysis revealed a main effect of Action-type ($F1(1,41)=17.2$, $MSE=10034$, $p<0.001$; $F2(1,26)=12.5$, $MSE=6538$, $p<0.01$). Also seen was a three-way interaction of Group by Action-type by Viewpoint that reached significance by subjects only ($F1(2,82)=3.56$, $MSE=7163$, $p<0.05$; $F2(2,52)=2.16$, $MSE=3837$, $p=0.13$).

Analysis of accuracy found only a main effect of Viewpoint that was significant by items and marginally significant by subjects ($F1(1.87,76.5)=3.11$, $MSE=0.027$, $p=0.054$; $F2(1.67,43.3)=6.38$, $MSE=0.030$, $p<0.01$).

Table 4 provides a summary of the results by group. The main effect of Action-type was due to the fact that signs led to less priming than gestures (153 vs. 205 ms). The main effect of Viewpoint in the accuracy analysis reflects differences in accuracy among responses to targets preceded by Front-, Left- and Right-view primes (97.8%, 98.7% and 99.8% respectively; only the F-R comparison reaches significance, $p<0.01$).

The presence of a three-way interaction in the priming analysis, as was found here, is just what would be predicted in the presence of an invariance phenomenon. However, follow-up comparisons related to this interaction do not provide much support for such an interpretation. Broadly, these follow-up comparisons show that both early and late signers showed more priming for gestures than signs (hence the main effect of Action-type). Although the magnitudes of the effects varied for different combinations of Viewpoint and Action-type, the most telling follow-up comparisons are those comparing the early and late groups. Pairwise comparisons here show that in all cases but one, priming magnitude did not differ substantially between the two groups. The one exception is for sign targets seen after Left-view primes, for which early signers showed more priming than late signers (171 vs. 106 ms, $p<0.05$). On the one hand, this difference means that priming is somewhat more stable across views for early than for late subjects (for the early group, only the F vs. R contrast reaches significance while for the late group, both the F vs. L and L vs. R contrasts do). Interestingly the relatively stable outcomes between viewing conditions were also seen for gestures. Therefore, although a three-way interaction is seen, it does not take the form that one would expect in the presence of a sign specific invariance phenomenon. Paralleling our analyses of the deaf vs. hearing groups conducted earlier, we now compare results for the early and late ASL learners in contexts in which Front-view primes preceded targets which themselves varied in Viewpoint.

3.4.2. Front-, Left- and Right-view targets preceded by Front-view primes

Variable-view targets	Priming (ms)				Accuracy			
	Viewpoint of target				Viewpoint of target			
Early	F	L	R	All views	F	L	R	All views
Signs	172	129	141	147	97.1%	99.5%	99.9%	99.2%
Gestures	207	113	193	171	99.3%	100.0%	99.8%	99.8%
Overall	190	121	167	159	98.4%	99.9%	99.9%	99.6%
Late								
Signs	172	83	107	121	97.3%	100.0%	99.8%	99.5%
Gestures	206	136	156	166	96.8%	98.6%	99.7%	98.6%
Overall	189	109	131	143	97.0%	99.6%	99.8%	99.1%

Table 5. Overview of priming and accuracy means for the early and late learners of ASL, for Front-, Left- and Right-view targets preceded by Front-view primes.

In this analysis, we examine the cases in which primes were seen in the Front view and targets varied as a function of Viewpoint (Front, Left or Right), in a three-way analysis with factors of Group (early vs. late learners); Action-type (sign vs. gesture) and target Viewpoint (Front, Left or Right). In this priming analysis we observe main effects of Action-type ($F1(1,41)=12.2$, $MSE=6176$, $p<0.01$; $F2(1,26)=6.83$, $MSE=5543$, $p<0.05$) and target Viewpoint ($F1(2,82)=28.7$, $MSE=4108$, $p<0.001$; $F2(1.72,44.8)=13.6$, $MSE=6010$, $p<0.001$). A two-way interaction of Viewpoint and Action-type reached significance only in the items analysis ($F1<1$; $F2(2,52)=3.20$, $MSE=5175$, $p<0.05$).

The accuracy data yielded one main effect and one interaction, both significant by items but only marginally significant by subjects: an effect of target Viewpoint ($F1(2,82)=2.43$, $MSE=0.017$, $p=0.09$; $F2(1.70,44.1)=15.7$, $MSE=0.015$, $p<0.001$), and a Group by Action-type interaction ($F1(1,41)=3.03$, $MSE=0.059$, $p=0.09$; $F2(1,26)=8.71$, $MSE=0.012$, $p<0.01$).

Mean results for the two groups are given in Table 5. The main effect of Action-type showed that overall, signs resulted in less priming than gestures (134 vs. 168 ms). The effect of Viewpoint reflects the fact that Front-Front pairs yielded the greatest priming (189 ms), followed by Front-Right pairs (149 ms), and with Front-Left pairs showing the least amount of priming (115 ms). Post-hoc comparisons showed that all of these differences were significant (p's<0.01). The Viewpoint by Action-type interaction that reached significance only in the items analysis was due to the fact that overall, priming differences between signs vs. gestures in the Left view did not reach significance for signs vs. gestures, but did otherwise (p's<0.05 for F and R targets). This outcome was broadly consistent between the early vs. late groups, however.

The accuracy data indicate that early and late signers' performance did not significantly differ on sign trials, but did on gesture trials (early and late learners, respectively: for signs 99.2% vs. 99.5%, ns; for gestures 99.8% vs. 98.6%, $p<0.01$). The ability for early signers to accurately detect differences between sign and gesture compared to the subtle yet significant difference in later learners is interesting and warrants further investigation. Overall, subjects were less accurate on Front-view target trials (97.8%) than on Left- or Right-view target trials (99.8% and 99.8%, p's<0.001 for the F vs. L and F vs. R comparisons).

As was the case in the analysis presented for the deaf and hearing groups in Section 3.3, the target stimuli themselves varied in viewpoint here, but in the presence of an invariance phenomenon, differences in outcomes between the deaf and hearing groups related to these manipulations of Viewpoint and Action-type would still be expected. Here again, however, we note the presence of a main effect of Viewpoint and the absence of a three-way Group by Action-type by Viewpoint interaction.

3.4.3. Discussion

In general terms, the results for the two deaf subgroups mirror those reported in the earlier analyses, with the largest effects being for Action-type (whereby prime-target pairs with sign stimuli led to less priming than gesture pairs) and prime and target Viewpoint. To the extent that interactions were found that might speak to our central research question (e.g. the weak three-way interaction seen in Section 3.4.1), similar outcomes were not seen in either the corresponding accuracy data, nor in the other analyses. Most importantly, this examination of the data from deaf signers has shown little evidence of differences as a function of age of exposure to sign language.

This lack of difference between groups is important because previous work has indicated that non-native signers show patterns of sign recognition differing from those of native signers. For example, data from Mayberry and Eichen (1991) showed that in the context of sign sentence shadowing and repetition, non-native signers were apt to make phonological errors, often rendering the sentences nonsensical, while native signers tended to make semantic substitutions that, nevertheless, preserved the overall gist of the sentence content (see also Mayberry & Fischer, 1989). Further, Emmorey and Corina (1990) and Morford (personal communication) report that non-native signers were delayed in identifying signs in a gating experiment. In metalinguistic judgment tasks, Corina and Hildebrandt (2002) reported that natives and non-natives showed subtle differences in form-based similarity judgments of signs; native deaf signers rated movement as the most salient property while non-native signers were more influenced by handshape similarity. In summary, there is growing evidence to suggest that non-native signers may differ from native signers in the processing of form-based properties of signs. One interpretation is that non-native signers are less efficient in decoding the phonological forms of signs relative to native signers, for whom this stage of processing takes place in a more automatic fashion.

One implication of the present data is that the categorization task, while performed faster by deaf signers than hearing individuals, nevertheless does not strongly rely upon lexical access but rather upon pre-lexical visual representations of action forms.

The apparent *lack* of age of acquisition effects reported above is consistent with this supposition. Thus these data help us to understand the sequence of stages involved in sign processing and demarcate boundaries between general and language-specific visual processing of human actions.

4. General Discussion

In this paper we presented an analysis of data from a novel paradigm that pits the categorization of signs and gestures against one another in two groups of subjects: deaf signers, for whom sign serves as a primary means of communication, and hearing persons unfamiliar with sign language. The categorization paradigm was intended to illuminate the early stages of sign processing and specifically, to determine the extent to which experience with a sign language might lead to greater perceptual invariance as reflected in the magnitude of repetition priming effects. While we did observe group differences, whereby deaf subjects tended to be faster and more accurate than hearing subjects and evidenced less priming for signs relative to gestures, viewpoint changes generally modulated these effects in a manner that did not significantly differ for deaf and hearing signers. In both groups, we observed robust effects of viewpoint indicating that repetition priming for identical prime-target pairs was generally greater than in cases of categorization in which the prime and target varied in viewpoint. Subsequent analysis of deaf subjects segregated by age of exposure to ASL also provided little evidence for frank differences that could be interpreted as effects of perceptual invariance.

From these results, therefore, a consistent story emerges. In three out of our four priming analyses—those presented in Sections 3.2, 3.3 and 3.4.2—we noted main effects of Viewpoint that were unaccompanied by significant interactions of the kind that would be indicative of an invariance phenomenon. This was so for both of the comparisons of deaf vs. hearing subjects, as well as for one of the comparisons of early vs. late acquirers of ASL. In the remaining analysis, the comparison of early vs. late ASL learners given in Section 3.4.1, we did note a three-way interaction of Viewpoint with Group and Action-type. However, a closer look at the data indicated that this was a relatively local effect: magnitude of priming as compared between the early and late learners of ASL only differed significantly in one comparison (Front-view sign targets preceded by

Front- vs. Left-view primes). Similarly, the relatively weak Action-type by Viewpoint interaction observed in Section 3.4.2 showed no evidence of variation between the two deaf subgroups.

The one other interaction which we observed and which might be considered relevant to this issue is the marginally significant Group-by-Viewpoint interaction in the accuracy analysis noted in Section 3.2, where we reported the results for cases in which Front-view targets were preceded by primes of various viewpoints. There, we found that deaf subjects showed a more stable performance in terms of accuracy than hearing subjects. However, this was not modulated by Action-type; moreover, it was not generally reflected in other analyses. Suggesting the effect, if present, is not sign-specific. Although we cannot rule out the possibility that an invariance phenomenon may have had some kind of influence in subjects' performance of this categorization task, the preponderance of the evidence does not support this interpretation.

One possibility that should be acknowledged is that this experimental paradigm was not sensitive or powerful enough to reveal the presence of such a phenomenon at work. However, evidence of this paradigm's effectiveness can be found, for example, in the initial analysis in Section 3.1, where we verified that priming was occurring in the expected way (reduced RTs to repeated actions and not in general otherwise), and in the Group by Action-type interaction for RT, showing that deaf responses to signs were significantly faster than to gestures, with no such significant difference seen in the hearing group. Highly significant effects of Viewpoint were also found readily. Therefore, if effects of invariance are in fact at work in this categorization task, it seems that they would have to be quite subtle.

These results have implications for models of sign language processing. As previously noted, we know little about the initial stages of sign recognition and the extent to which this differs from stages involved in the recognition of non-language gestures. While experience with a sign language may improve the ability to categorize signs versus gestures, we see little evidence for a perceptual invariance effect for through-plane rotation in this task. The current results suggest that at the earliest stages, the perceptual processing required for identification of signs versus gestures does not substantially differ.

One question worth pursing in subsequent studies is whether the use of a lexical decision task using signs and non-signs[14] as stimuli, rather than the sign/gesture categorization task used here, might result in a different outcome. In addition, the use of techniques such as event-related potentials (ERP) and/or magneto-encephalogram (MEG) methodologies may provide opportunities for further differentiating the time course of these processes.

It is interesting to note that differences in properties of visual movement discrimination and visual-spatial processing of sign trajectories have been reported between deaf and hearing subjects (see Bavelier, Dye & Hauser, 2006; Poizner, Bellugi & Lutes-Driscoll, 1981). Note however that these studies have either used low-level psychophysical displays under unique viewing conditions or extracted properties of sign forms (as in the case of point-light displays used by Poizner et al, 1981). An important way in which the present study differs from these earlier studies is in our use of naturalistic stimuli.

We should note that in its strictest sense, orientation-specificity could be taken as implying that identical actions seen from different viewpoints should lead to no priming at all, or perhaps even to inhibitory effects. Clearly this was not the case in the present study, in which priming values were consistently positive. Moreover, we also found that different viewpoints were not always associated with significant differences in priming (or accuracy) in all of our follow-up pairwise comparisons, despite the nearly-ubiquitous appearance of main effects of Viewpoint. We interpret these results as suggesting that strong physical—and therefore perceptual—similarities in actions seen from different viewpoints (as in our stimuli) can result in some activation of representations of same actions seen from different points-of-view, though this activation is weaker than in cases where both action and point-of-view are shared. For instance, even a hearing non-signer could recognize that adjacent video clips showing an identical sign from different points of view shared the same action, and hence would tend to show priming in the second appearance of the action when making a categorization.

Within the domain of visual processing of human actions, researchers using static stimuli have reported that reliable priming effects are obtained only when priming and primed poses or (implied) actions share the

[14] Non-signs are phonologically legal items that happen to be non-occurring in the lexicon, as opposed to the fully non-linguistic grooming gestures that were used in the present study.

same in-depth rotation or are seen in Left-Right reflection. Having seen the same action or pose in a different orientation did not reliably facilitate identification later on (Daems & Verfaillie, 1999). These data are taken as evidence that stored representations that mediate the identification of human actions and postures are viewpoint-specific. Our data are largely consistent with and extend these findings in two major ways. First, in contrast to the work by Daems & Verfaillie (1999), who used static images of postures and implied actions, we observe viewpoint-specific results for dynamic stimuli. These dynamic stimuli which show maximal priming effects under viewpoint identical conditions, are not however absolute as measurable repetition priming does occur across non-identical viewpoints. Second, our data suggest that significant linguistic experience with a class of human actions (i.e. signs) does not fundamentally change this perceptual constraint.

5. Conclusion

The present study found that when required to categorize signs and non-linguistic gestures, deaf signers and hearing non-signers showed repetition priming effects that varied in different viewing conditions, but showed patterns that were similar between groups. The same pattern held for early- and late-exposed signers. These outcomes indicate that initial stages of sign and gesture recognition required for the categorization of action-types do not differ as a function of experience with a signed language. Instead, our data are consistent with and extend previously described visual-perceptual studies that have reported evidence for orientation-specific representations of human actions.

Appendix: List of Stimuli

Gestures	Signs
Adjust Shirt	BACHELOR
Brush Hair	BEER
Crack Knuckles	BITTER
Pull Ear	DOLL
Rub Eye	GLASSES
Rub Nose (Signer 1)	HOME
Rub Nose (Signer 2)	ISLAND

Scratch Face	LIKE
Scratch Head (Signer 1)	NATURALLY
Scratch Head (Signer 2)	ORANGE
Scratch Neck	PARENT
Scratch Nose	TREE
Stretch Arms	WEEK
Tug Shirt	WONDER

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