Interacting with Computers 21 (2009) 243–256

Contents lists available at ScienceDirect

Interacting with Computers

journal homepage: www.elsevier.com/locate/intcom

Technology for supporting web information search and learning in Sign Language

Inmaculada Fajardo [a,*], Markel Vigo [b], Ladislao Salmerón [a]

[a] Department of Developmental and Educational Psychology, University of Valencia, Blasco Ibañez, 26010 Valencia, Spain
[b] Department of Computer Architecture and Technology, University of the Basque Country, Manuel Lardizabal 1, 20018 San Sebastian, Spain

ARTICLE INFO

Article history:
Received 1 October 2008
Received in revised form 9 March 2009
Accepted 12 May 2009
Available online 21 May 2009

Keywords:
Web accessibility
Deafness
Sign Language
Information search
e-Learning
Video Technology

ABSTRACT

Sign Languages (SL) are underrepresented in the digital world, which contributes to the digital divide for the Deaf Community. In this paper, our goal is twofold: (1) to review the implications of current SL generation technologies for two key user web tasks, information search and learning and (2) to propose a taxonomy of the technical and functional dimensions for categorizing those technologies. The review reveals that although contents can currently be portrayed in SL by means of videos of human signers or avatars, the debate about how bilingual (text and SL) versus SL-only websites affect signers' comprehension of hypertext content emerges as an unresolved issue in need of further empirical research. The taxonomy highlights that videos of human signers are ecological but require a high-cost group of experts to perform text to SL translations, video editing and web uploading. Avatar technology, generally associated with automatic text-SL translators, reduces bandwidth requirements and human resources but it lacks reliability. The insights gained through this review may enable designers, educators or users to select the technology that best suits their goals.

1. Introduction

According to the World Health Organization, 278 million people in the world are deaf or hard of hearing (World Health Organization, 2006) and many of them have Sign Language (SL) as their mother language. The diversity of regional variations of SL constitutes a set of minority languages relatively underrepresented in the digital world. Thus, members of the Deaf Community usually face non-native language web sites where accessibility barriers may emerge (e.g. Fajardo et al., 2006; Smith, 2006).

In order to ensure the Deaf Community's social inclusion, SL has to be properly incorporated into Information Technologies. Furthermore, as Kralisch and Berendt (2005) highlight, the web inclusion of minority languages might not be only an ethical but a commercial issue, related, for instance, to financial investment to create bilingual websites. In Spain, there are around 400,000 users of Spanish Sign Language (INE, Instituto Nacional de Estadística, 2006) who use oral and written Spanish as a second language and could benefit from inclusive policies. Spanish and Catalan Sign Languages have held the status of State Official Languages in Spain since 2007, as is also the case in other Member States of the European Union.

The World Wide Web Consortium (W3C) addresses, to some extent, deaf users' issues in the Web Content Accessibility Guidelines, WCAG 1.0 (Chisholm et al., 1999). In particular, Guideline 1.4 recommends that audio and its textual transcription should be synchronized, while guideline 14 states that deaf users would benefit from simple and clear written language. Besides the vagueness of these guidelines, it is important to note that they just deal with the captioning or text transcription of auditory content, leaving out the visual–spatial characteristics of SL, thus causing information loss. In addition, as clear implementation techniques are not provided, non-experts find it difficult to create WCAG-compliant web pages for the Deaf. WCAG 2.0 (Caldwell et al., 2008) became a W3C candidate recommendation in December 2008. As opposed to WCAG 1.0, SL issues are more extensively addressed in this set of guidelines. Guideline 1.2, entitled "Time-based Media: provide alternatives for time-based media", is one of those guidelines whose fulfilment enhances web content *perceivability* by users, including the deaf. Specifically, success criterion 1.2.6 states "*Sign Language interpretation is provided for all prerecorded audio content in synchronized media*". Satisfying success criterion 1.2.6 is necessary in order to meet the most demanding conformance level, the AAA success criteria. Specifically, it claims to provide SL interpretation for synchronized media by means of the following techniques:

- Embedding a SL interpreter in the video stream in order to provide SL transcription of audio content.

* Corresponding author. Address: Avda. Blasco Ibáñez, 21, 46010 Valencia, Spain. Tel.: +34 963983847.
E-mail addresses: infabra@uv.es (I. Fajardo), markel@si.ehu.es (M. Vigo), Ladislao.Salmeron@uv.es (L. Salmerón).

0953-5438/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.intcom.2009.05.005

– Techniques and examples of synchronizing video of the SL interpreter in order to display it in a different overlay on the image using SMIL (Michel, 2008) technology.

However, this success criterion just focuses on the transcription of auditory content. Nothing is mentioned about link content or content transcription, which, most of the time, is not auditory but textual.

In order to ensure accessibility of digital resources such as the World Wide Web (WWW), many countries have introduced laws in this regard.[1] Identifying levels of conformance with guidelines is of paramount importance, as most policies rely on standards such as the above-mentioned WCAG or similar. However, the most demanding levels of compliance, including those referring to deafness, are seldom required in order to meet these policies.

In addition, government initiatives and *standardista* contributions cannot be effectively applied if they are not accompanied by research conducted in different areas such as Human–Computer Interaction, Computer Science, Psychology, or Sociology. These scientific disciplines could help to answer questions such as the following, quoted from Cunliffe and Herring (2005, pp. 135–136):

1. How should the impact (whether positive or negative) of technology in minority language use be measured and quantified?
2. How can the linguistic dimensions of the digital divide be measured and how can its significance be assessed?
3. How does interface design influence language behaviour, e.g. how can design be used to promote minority language use in bilingual contexts, or to better support users accessing content in their non-native language?

Or, added by us:

4. What kind of technology is available and how appropriate is it to include SL on the web?
5. How do SL technologies affect the information scent (assessment of the semantic similarity between searching goals and hyperlink choices) and knowledge acquisition on the web?

Although it is vital to find the answers to all of these questions, the objective of this article is principally to answer the last two. Therefore, the aim of the following sections is to shed some light on how current SL technologies can provide deaf users with a satisfactory user experience while interacting with the WWW. Note that some of the prototypes presented were not intended for the WWW but they are mentioned in this paper as their foundations are sound and can be deployed in web environments.

Section 2 describes the most relevant SL generation systems for the web, emphasizing their strengths and weaknesses with regard to their usefulness for web information search. Similarly, the same procedure has been followed in Section 3, focusing on web learning. In Section 4, based on the previous systems review, we propose a taxonomy that classifies SL generation systems according to a set of relevant dimensions which are not only functional but also technical, such as location rendering, underlying technology (programming language, mark-up, etc.) or dimensionality. The purpose of the taxonomy is to help in the selection of the system or set of functionalities that best suits the goals of designers, educators or users while considering the availability of resources.

[1] Available at http://www.w3.org/WAI/Policy/.

2. Information search on the WWW by means of Sign Language

A web document or hypertext system is composed of a set of information nodes connected by links or hyperlinks. Information search refers to the user's behaviour when looking for pieces of information within or between web pages or hypertexts by means of queries in search engines and/or by following hyperlinks. Whatever the mechanism used, one of the most influential theories of information search, the Information Foraging Theory (Pirolli and Card, 1999), predicts that a particular hyperlink will be followed when the trade-off between information gained and cost of access is low. Therefore, in order to calculate such trade-offs, individuals have to assess the semantic similarity between the search goals and hyperlink choices (called information scents) presented on a web page or in a hypertext node. As Pirolli (2004) found, users seem to use semantic scents for judging not only when visiting a website but also when leaving it.

The obvious problem for SL users is that semantic cues are commonly only available in a non-native language (link words) in which they present low levels of reading proficiency (e.g. Leybaert et al., 1982; Alegría, 1999; Asensio, 1989; Goldin-Meadow and Mayberry, 2001). Consequently, deaf signers find it difficult to use a scent following strategy with textual cues as some empirical studies seem to indicate (Fajardo et al., 2009). Apparently, an easy solution to increase information search for deaf signer users is the use of graphical hyperlinks or icons, since they facilitate the process of semantic decision-making according to the classical Picture Superiority Effect (Nelson et al., 1976; Paivio, 1991). In addition, Namatame et al. (2007) observed that deaf participants were even more accurate than hearing participants in a simple visual search and match task where participants were asked to pair directory names, typically used in representative web sites, with pictograms (Experiment 2). In contrast, Fajardo et al. (2006) did not observe accuracy differences between deaf and hearing users with using graphical material. Across two experiments, users were asked to find targets in a hypertext system with several layers of nodes (a more complex search task than in Namatame et al.). Although deaf users were faster in a graphical than in a textual hypertext, deaf and hearing participants were equally accurate when very familiar and frequent pictures were used as hyperlinks (Fajardo et al., 2008a). When unfamiliar pictures were used as hyperlinks, both types of users found less targets, were slower and became more disoriented in the graphic hypertext than in the textual hypertext (Fajardo et al., 2006). Therefore, it seems reasonable to assume that SL scent cues could be a more appropriate solution for improving deaf signers' information searching than text or icons, but here we find a technological issue: is there any technology available to provide SL scent cues? As described in the following sections, we distinguish between mechanisms for making it possible to follow hyperlinks in SL and mechanisms for supporting queries in SL (for an extended description of this functional dimension for SL generation techniques, see the dimension *Task* in the taxonomy proposed in Section 4).

2.1. Hyperlinking by means of Sign Language

To enable not only content access but link-following in SL, a number of research projects have developed a set of more or less sophisticated techniques. Starting with an apparently simple idea, the Cogniweb project (Fajardo et al., 2008b,c) developed two alternatives consisting of videos embedded in small frames which contain SL translation (performed by human signers) of each textual hyperlink in the menu. This mechanism is called *Sign Language Scent* (SLS) here. In the first approach, when the cursor hovers over a link, the embedded video located at the left-bottom of the page

starts signing so that the user grasps the meaning of the link (see Fig. 1, left). In the second approach, every link is related to its own video that signs whenever the user clicks on it (see Fig. 1, right). In two experiments (Fajardo et al., 2008b,c), it was observed that deaf signer users were more efficient with the second version. Furthermore, deaf signer users became less disorientated (measured by the number of page visited per search) and were less dependent on their verbal categorical reasoning abilities using SLS than just using textual hyperlinks. These results would represent empirical support for the usage of SL videos linked to textual hyperlinks as an efficient web navigation mechanism for deaf signer users.

These two approaches were aimed at providing both SL and text information scent cues; that is, to support bilingual navigation. It is a desirable goal from the point of view of the *Access for All* principle, but quite challenging from a technical viewpoint. One of the main limitations of the Cogniweb Project is the lack of an authoring tool to support video processing and web page edition, two tasks that require high expertise and are highly time-consuming.

Other more sophisticated approaches are aimed at creating web sites exclusively in SL, which would allow both content access and navigation in this language. These approaches are based on the Hypervideo technology which consists of links inserted in videos so that the user can retrieve further information about concepts conveyed in certain sequences. Links are represented by means of text or a static image, which may not convey SL concepts in a proper manner. Based on this technology, Fels et al. (2006) developed the *Signlinking* system. Each *Signlink* is a period of time within the video clip, defined by the author. When the video reaches a *Signlink*, a link indicator is displayed to notify the user. Then, the user can click and follow the link or continue playing the content.

A similar approach is followed in a system designed by Kaibel et al. (2006). In this system, the user can get an overview of the hyperlink videos by hovering the mouse over each snapshot. In addition, there is a hand or a text-symbol at the bottom-left of each hyperlink video indicating which type of document the hypervideo leads to. A video containing a hand-symbol leads to a SL page whilst a video that contains a text-symbol will lead to a traditional hypertext document.

It is not clear which of these two approaches to hypervideo for SL navigation is more effective. Regarding *Signlinking*, throughout successive re-designs of the system, in the sequence where the signer was referring to the concept requiring a hyperlink, the link indicator evolved from a red rectangle surrounding the upper torso of the signer to a small red icon located at the top-left corner of the video window. Two usability studies showed that deaf signer participants were confused about the meaning of the red rectangle while navigating through signed web pages (study 1). However, the understanding of a different group of users improved and number of navigation errors decreased after replacing the rectangles with the arrow-into-document icon (study 2). As the authors admit, these two studies helped to improve the design of the video link indicators and other elements such as video link density indicators in a video but some important questions remain unanswered. For instance, with regard to the advantage that this kind of technology could bring to deaf signers compared to a text-only version of a website: do video-link web pages improve the link-following strategy of signers compared to traditional text-link web pages? This question, as is the case with most of the questions highlighted throughout this article, can only be resolved by means of experimentation.

2.2. Queries in Sign Language

In addition to the hyperlink-following strategy, a complementary mechanism for searching for information on the web is the use of queries in search engines. Taking into account the tridimensionality of SL and the fact that it cannot be alphabetically sequenced, most of the multimedia dictionaries for signers use query systems that just allow users word-to-SL search.

In order to overcome this limitation, Vettori and Felice (2008) developed e-Lis (see Fig. 2 for a snapshot of the system), which allows signers to make queries in SL, in a SL-Italian/Italian-SL dictionary. A notable feature of e-Lis is that its dialogue allows users to make queries using signs by selecting their formational units. However, instead of 3D avatars, pre-stored 2D pictures are used.

Buttussi et al. (2007) aim at providing holistic search tools using 3D virtual avatars for word-to-SL, SL-to-word and SL-to-SL searches with 3DictSL. The purpose of the SL-to-SL search is to find equivalent signs in different SLs. The SL-to-word or SL-to-SL are the more challenging tasks and signs are introduced by successively selecting 3D formational units of a sign or cheremes; i.e. the hand shape, orientation, location and movement of the palm. They also provide online authoring tools for creating new dictionaries where

Fig. 1. Examples of the two versions of web page with textual hyperlinks supported by SL videos used in the Cogniweb project. In the version on the left, videos with corresponding translation of the textual hyperlinks were presented in a unique frame of the screen placed in a distant location. In the version on the right, videos were placed close to each hyperlink. The videos were activated by clicking or passing the mouse cursor over the hyperlink.

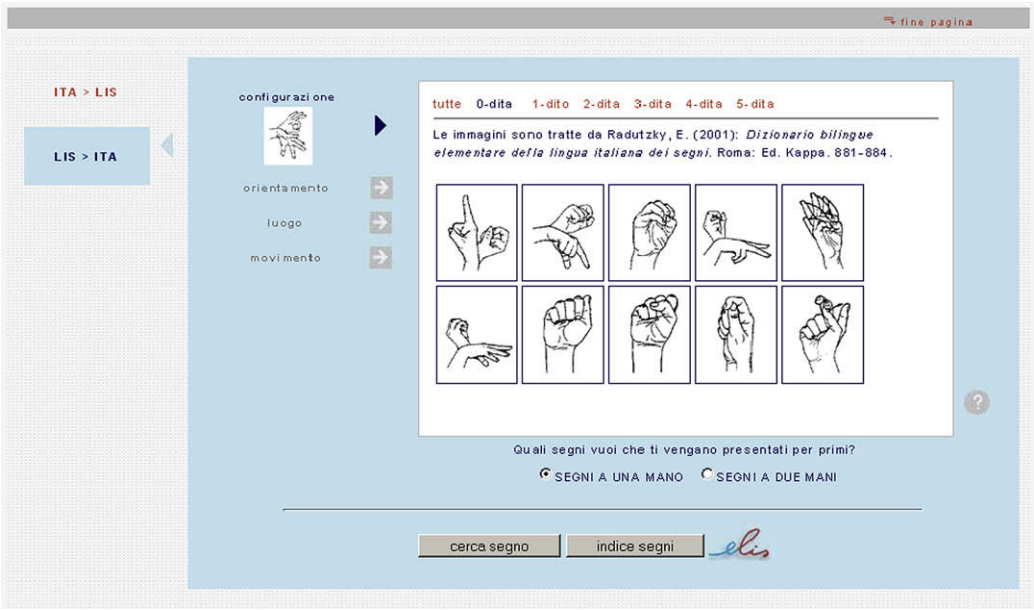

Fig. 2. e-Lis Dialogue for making sign enquiries using formational units (Vettori and Felice, 2008).

new signs can be stored by composing existing cheremes. However, the creation of a new dictionary from scratch turns out to be a cumbersome task for a small group of experts.

Among other factors, it would be necessary to test the understandability of the 3D signs transmitted by avatars in 3DictSL versus 2D pictures in e-LIS versus written text, and the usability of the search-by-chereme interfaces. To date, none of these two approaches that aim at making queries in SL possible have been validated empirically which seems to be the common limitation of most of the techniques we describe in this article.

3. Web learning in Sign Language

Web and hypertext learning research is mostly, although not exclusively, focused on reading comprehension. Reading comprehension in hypertext refers to the process of knowledge acquisition from the texts provided on websites and in hypertext systems. The construction–integration model of text comprehension (Kintsch, 1988, 1998; Van Dijk and Kintsch, 1983) frames most of the research on hypertext comprehension (see a review by Salmerón et al., 2005). According to this model, the reader generates two mental representations from the text: the textbase (a propositional representation of the information within the text) and the situation model (a representation of what the text is about which integrates the information with the readers' prior knowledge). Unlike traditional printed materials, hypertext systems are characterized by a non-linear structure of information which allows an active learning process, making users select the pieces of text to read next. The idea that the user controls the reading process may sound appealing, but the fact is that hypertext may be beneficial only when the readers can rely on their reading skills to deal with the multi-linearity of hypertext (Foltz, 1996). This fact becomes especially relevant for the majority of prelingually deaf people, who usually show low levels of reading proficiency (e.g. Leybaert et al., 1982; Asensio, 1989; Alegría, 1999; Goldin-Meadow and Mayberry, 2001). Quoting Foltz, "*readers with poor reading skills are using a lot more controlled processing for their reading processing and thus will likely have a greater amount of interference from the additional task of navigating the text*". This will not let them generate as many inferences about the text as they read it, making it harder to integrate the information.

One alternative to overcome the poor reading skills of deaf users may consist of translating written information from hypertext into SL, as in ViSiCAST by Elliott et al. (2000) and eSign by Kennaway et al. (2007). The idea of providing content in SL seems to be a viable solution but again generates many questions: how can hypertext content be provided in SL? How does SL affect the comprehension of text? Should SL content entirely replace the texts or just support them? Do bilingual web sites enhance or interfere with deaf people's content comprehension? Is it feasible to translate all hypertext content to SL? As a young and relatively illiterate language, is the SL vocabulary suited to conveying the technical or scientific concepts of some academic subjects and formal documents? In the next two subsections (3.1 and 3.2), we describe the advantages and weaknesses of technologies based on bilingual versus SL-only approaches which has been a long-standing debate in deaf education.

3.1. Bilingual (sign plus text) web sites

Digital video technology has allowed the incorporation of SL into the web by providing SL translations of texts performed by human signers or avatars. The two most popular ways of displaying the SL video that translates the text are: (1) in a different browser window (see example in Fig. 3); and (2) embedded in the same web page as that in which the text appears (see example in Fig. 4).

Far from being a trivial issue, the choice between these two options might have important repercussions on the learning process. Research conducted with hearing users in the field of multimedia learning may serve as a guide for evaluation of the usability of theses video technologies. In particular, two principles emerge as relevant to our goal: the spatial contiguity (Mayer, 2005) and redundancy (Sweller, 2005) principles.

According to the spatial contiguity principle, the user's understanding of the message transmitted through words and corresponding pictures will increase when they are presented near to each other, rather than far apart from each other on the page (Mayer, 2005). If we apply this principle to the understanding of the text and corresponding SL translations, we would expect that the embedded video approach would be superior to the separate pop-up windows approach, because the text and the SL videos are more closely linked.

Fig. 3. Example of SL videos displayed in a separated pop-up window from http://www.diariosigno.com.

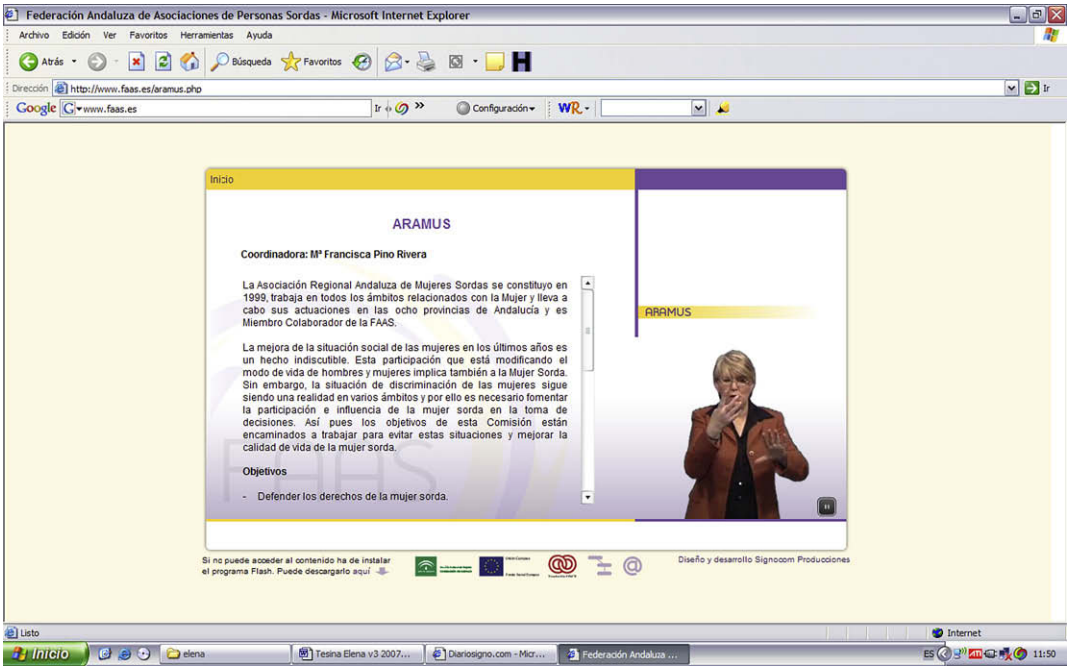

Fig. 4. Example of SL videos displayed in an embedded frame from http://www.faas.es.

On the other hand, the redundancy principle states that hearing users' comprehension is hampered if the multimedia system includes different sources of the same information, e.g. graphics and redundant texts. A possible explanation is that in these situations readers are forced to divide their attention between the sources of information (both presented in visual format in the aforementioned example), thus increasing the cognitive load of the task. In the case of SL hypertext, including both the written information and the exact SL translation at the same time may hamper deaf users' comprehension. In addition, as Richards et al. (2005) highlight, having to pay attention to different sources would create literacy barriers due to the continuous switching between their language of choice and a second language. The redundancy issue could be even more relevant for deaf learners because they commonly exhibit difficulties integrating information coming from two differences sources (Marschark et al., 2006). This redundancy problem would affect both embedded and separate videos, but it could be mitigated by enhancing the text–sign synchronisation.

Fig. 5. Example of sign-text synchronization using Videotext.web technology, retrieved from http://www.oegsbarrierefrei.at/.

In that sense, Videotext.web (Austrian Sign Language Service Centre[2] and the Indeed![3] company) enables designers to highlight the sentence of the text that is being signed in the video (see Fig. 5). However, even if *a priori* it is a feasible approach, it has not been empirically tested and could generate more problems than solutions.

In general, one important question which emerges from the technological solutions mentioned up to now is how bilingual websites may affect signers' comprehension of hypertext content. This issue has actually unleashed a great debate and much research in the context of education for deaf children. In particular, in order to test whether multimedia technology can improve the text comprehension of deaf students, Gentry et al. (2004/2005) conducted an experiment in which deaf participants were presented stories in 4 different formats: printed, printed plus pictures, printed plus SL, and printed plus pictures plus SL. The lowest comprehension scores, measured by means of a story retelling activity, appeared for the printed-only condition, while the printed plus pictures condition obtained the highest scores. The use of signs improved performance compared to the text-only condition but not to the printed format plus picture condition. The authors suggest that an explanation for that is that deaf children develop meta-cognitive strategies to decode text by using pictures, because pictures have been traditionally used in deaf education. However, they would not have this type of strategy available to decode text using SL, due to a lack of practice.

Thus, in order to facilitate development of meta-cognitive strategies for decoding text using signs, literacy teaching for deaf children should be supported by this kind of multilingual approach in the early stages of education. Similarly, we could argue that bilingual (text and SL) access to hypertext content would be improved through practice with the kind of new emerging technologies presented here. Longitudinal studies would be needed to answer this question.

This explanation of the phenomenon based on the peculiarities of deaf students' instruction is sound but, as we noted before, if the design of text plus pictures material fulfils the contiguity and redundancy principles, hearing learners would also be able to take advantage of the picture and texts combination (Mautone and Mayer, 2007; Moreno and Mayer, 2002). Actually, adjunct pictures to text have been frequently used in instructional material (both for printed books and computer-based material) for hearing student education. That means that a more general factor could be explaining the superiority of text plus pictures in deaf people. However, to our knowledge, there are no studies which directly compare deaf and hearing students regarding the facilitative effect of picture aids on comprehension, which, once again, moves this idea into the category of interesting hypothesis for future testing.

A third alternative explanation for the superiority of text plus pictures over SL-only material in deaf learners is based on the fact, highlighted above, that SL is a young and relatively illiterate language and consequently may lack the terminology (vocabulary) to translate or express the technical or scientific terms common in some academic disciplines, such as biology or mathematics. We could argue that SL users would prefer precise terms in their second language to ambiguous and inappropriate terms in their mother tongue.

Dowaliby and Lang (1999) performed a comprehension study with 144 deaf college students using a scientific text on the topic of "The Human eye, its function". They compared five instructional conditions: (1) text only, (2) text followed by content videos (a video showing a visual example of the information) (3) text followed by sign videos (a video of the text signed) (4) text followed by adjunct questions (a written practice question after each text and

[2] http://www.oegsbarrierefrei.at/ (last accessed on February 2009).
[3] Indeed! available at http://www.indeed.at/web/products/ (last accessed on February 2009).

feedback on the response) and (5) all of these together (full condition). Although they did not report any difficulty related to the translation of the scientific text to English-like signing with American Sign Language, the performance of students provided with a text-only version of the information was similar to those who studied the written text plus a signed video of the information. Although these results may be partially interpreted in terms of a "lack of technical terminology" hypothesis, future usability studies should include a version with a signed video only to clearly compare the effectiveness of both written and signed languages in supporting the comprehension of scientific texts.

Nevertheless, the study by Dowaliby and Lang (1999) demonstrates that technical supports that facilitate deaf students' comprehension of narrative stories, such as adjunct pictures (Gentry et al., 2004/2005), may not be so effective for supporting the reading of a technical text. The authors constructed a third version of the scientific text on the 'Human eye' which included the written text plus a video showing a visual example of the information. Contrary to what has been found for narratives, this version did not improve comprehension. Indeed, the best condition to foster scientific comprehension in their study was the written text plus adjunct questions (a written practice question after each text and feedback on the response).

In summary, there are technologies and procedures for generating bilingual (sings plus text) web sites but, according to the empirical insights gained until now, to foster deaf readers' comprehension of the narrative content of web sites, adjunct pictures are more effective than adjunct SL. Future research will help to test new procedures to effectively combine both types of information. In the meantime, existing technology may support the creation of SL-only web sites instead of bilingual approaches, so the next question is *could the exclusive use of SL foster content comprehension, instead of the use of SL as adjunct or complementary information?* This could be a way of reducing the impact of redundant information coming from different sources and in need of integration. Let us answer this question in the next section.

3.2. SL-only web sites

Hypervideo technology, introduced in Section 2, makes it possible to embed clickable anchors in video streams, allowing the development of sign-only web sites. As described above, Fels et al. (2006) developed an authoring tool for creating *Signlinked* web pages in which both the content and navigation mechanisms could be provided exclusively in SL The educational potential of this approach could be enormous but, as we argued in the previous section, there are still no empirical studies proving its validity to improve, for instance, deaf signers' comprehension of academic material.

From a human resources perspective, one of the main disadvantages of the use of human signers is that it is necessary to have a group of experts available for the translations from text to SL, recording, editing and uploading videos to the web. A solution to this problem would be the use of SL transcriptions but due to, among other factors, the visual–spatial and temporal nature of the SL, its transcription turns out to be quite complex. However, there are some widely accepted notation systems. For example, Stokoe (Stokoe, 1960) for American Sign Language, Hamburg Notation System, HamNoSys (Prillwitz et al., 1989) or SignWriting (Sutton, 1977) can be used for such a task. These notation systems represent the basic parameters of signs (movements, hand shape and location) by means of pictograms. They are often used by advanced automatic SL generators as intermediate representation of real signs (Kennaway et al., 2007). They are also useful for small screens and for devices with limited computing resources. On the other hand, these notations have to be learned, which can be as difficult as learning a written language. In order to find a more economical and less time-consuming method of producing SL material compared to the expensive human signers' videos or the difficult to learn notation systems, several groups are developing different solutions to automatically translate text to SL and synthesize it using avatars.

ViSiCAST by Elliott et al. (2000) was one of the preliminary projects that aimed at providing signing avatars on the World Wide Web (WWW). Aimed at achieving that developers adopt SL generation technologies, its creation could not entail a large amount of financial investment or development effort. However, ViSiCAST required motion capture techniques to record the body, hand and face gestures of a human signer. These captures were then converted into highly realistic animations which were stored in a database of reusable signs. Therefore, in order to find a solution to this costly process of motion capture, ViSiCAST evolved into the eSign project. Using an XML-based language called Signing Gesture Markup Language (SiGML) it was decided that once a browser plug-in was developed for such language, an avatar would transcribe a web page into SL. The SiGML-to-avatar philosophy provides the framework with a set of tools for content creation. The avatar is rendered on the user's computer; saving the bandwidth that video broadcasting would otherwise require. Kennaway et al. (2007) report the results of a set of studies, conducted in three different countries, to test the quality of the synthetic signs developed in the e-Sign project. The recognition rate by native Sign Language users was around 95% for single signs and ranged between 35% and 58% for signed sentences and chunks of text. These results support the use synthetic signs for single words mainly. However, those studies were conducted with small sample sizes and important methodological details such as the number of trials per test, length of sentences and order of presentation are not reported, which reduces the generalization and validity of the results. In addition, the tools for content creation are domain dependent (weather forecast or online employment office) and if the plug-in is not supported by the user's browser, the video content will be downloaded instead. Therefore, the user cannot take advantage of one of the key features of the system, which is low bandwidth SL generation.

As far as on-the-fly SL creation is concerned, Francik and Fabian (2002) developed a real-time humanoid avatar that signed Polish SL in real time. It consists of a humanoid that lacks facial expression.

Huenerfauth (2008) goes one step further, applying the latest Machine Translation technologies for an efficient automatic SL generation that considers the Classifier Predicate phenomenon (CP). CPs are those SL phenomena that "make use the space around the signer in a topologically meaningful way" (Huenerfauth, 2008). Huenerfauth et al. (2008) designed an experimental study to compare the effectiveness between their CP-aware system and Signed English animations (words in an English sentence were replaced with their corresponding signs without taking into account the SL grammar). They found that American Sign Language (ASL) users judged the CPs transmitted by their system significantly more natural, grammatically correct and understandable than Signed English. In addition, the CP-capable system proved to be more effective than the Signed English animations as ASL users were more accurate in selecting the corresponding animated visualization (out of three animations) that both systems aimed at transmitting.

In conclusion, both hypervideos with human signers and avatar technology can offer web content exclusively in SL and could solve the language switching problems which could emerge in bilingual contexts. Paradoxically, SL-only approaches might not be as effective in facilitating the comprehension of academic information by deaf students (e.g. Marschark et al., 2006; Rodriguez-Ortiz, 2007) as oral languages are for hearing students. That is, the level of

comprehension obtained by hearing students exposed to spoken lectures is higher than the level of comprehension of deaf students exposed to signed or interpreted lessons.

For instance, Marschark et al. (2006) compared the effect on the comprehension of two academic lectures (one on soil mechanics and one on visual perception) by deaf signer students using real-time text transcriptions, SL interpreting and both (Experiment 1). They found that real-time text alone significantly improved the performance of deaf students compared to the other two conditions. The rest of experiments reported failed to replicate the real-time text advantage but they did find that the deaf students' performance in all conditions was below that of the hearing students who received oral lectures. Rodriguez-Ortiz recently conducted a study to evaluate to what extent deaf individuals understand Spanish Sign Language interpretation. She found that signing deaf participants extracted less information than hearing signer participants from academic oral lectures (domestic violence and apartment searching for university students). These results replicate Marschark et al.'s findings (Experiment 1), but, using more complete measures of comprehension (text based, inferences, etc.). Rodriguez-Ortiz suggests differences in discourse processing strategies as a possible explanation for the difference between hearing and deaf people (Banks et al., 1990), as well as less language exposure during childhood and the later acquisition of spoken language, which could determine the acquisition of meta-comprehension abilities.

Alternatively, these results could again be explained by the "lack of technical terminology in SL" hypothesis, referred to in the previous section. Actually, although Marschark et al. (2006) used introductory-level lectures, the topics were highly specific (soil mechanics and visual perception). The topics used by Rodriguez-Ortiz (2007) possibly involve a more common vocabulary (domestic violence and apartment searching for university students) but with no information about the word frequency or the validity of the SL terminology used in these experiments, this hypothesis is not falsifiable.

We are not aware of any empirical research comparing deaf learners' comprehension of academic content using SL-only material (not interpreted but recorded) versus regular texts (not real-time text transcriptions as in Marschark et al., 2006, nor transliterations). As mentioned earlier, a study of these characteristics would help to refute or support the hypothesis that SL is not a good vehicle to transmit academic content.

3.3. Towards a rational combination of SL and text

The hitherto discussed literature indicates that the use of complete SL webs, with either a bilingual or monolingual approach, could not directly improve deaf signers' access to web content. Therefore, we propose that future research efforts should move away from the dichotomy of SL webs versus written-text webs in an attempt to clarify which kind of information in textual webs should be translated into SL in order to foster deaf students' comprehension.

Within this framework, empirical studies should explore how key comprehension components can be supported by the inclusion of SL generation technologies. Oakhill and Cain (2007) have identified four components that explain comprehension of hearing students: vocabulary, inference making skill, comprehension monitoring, and understanding of text structure. We later discuss these issues with regard to deaf students' comprehension in SL hypertexts and propose a testable hypothesis for future studies.

The vocabulary and background knowledge has also proven to be an important predictor of deaf students' reading comprehension ability (Garrison et al., 1992). Thus, in order to activate background knowledge of deaf readers a testable alternative is the use of SL summaries presented before reading. This strategy improves the comprehension of easy narrative texts (fables) of deaf students (Andrews et al., 1994). Further studies should test the effectiveness of providing SL summaries in textual webs and others types of text (e.g. expositive, more complex narrative texts), for example, comparing deaf users' reading comprehension of web textual content with and without previous presentation of videos with SL summaries. This solution reduces the switching between languages and the redundancy of information sources (SL and textual), which could be counterproductive for deaf people, as discussed above.

Regarding the second component of reading comprehension, inference making can be improved by enhancing text cohesion. Along these lines, meta-textual elements (e.g. paragraphs, titles, headlines, etc.) are fundamental for textual cohesion in hearing readers (Rouet and Le Bigot, 2007). Therefore, bilingual webs should facilitate deaf students' identification of these elements by translating important meta-textual elements into SL. A potential usability experiment with deaf students might compare two types of informational webs: one including titles of news in a textual version, and a second using SL titles.

A third comprehension component that should be considered in bilingual educational webs for deaf students is the support for comprehension monitoring (i.e. assessment of one's own understanding during reading). We have already discussed the effectiveness of using textual adjunct questions during reading in fostering deaf students' monitoring and learning (Dowaliby and Lang, 1999). The extent to which this support can be enhanced by providing SL adjunct questions is still an open question for future research.

The last comprehension component considered, understanding of text structure, can be enhanced in SL hypertext systems by using graphical overviews or content maps, which display hypertext nodes and their relations. Graphical overviews have been used to promote the comprehension of hearing users (Salmerón et al., in press). Indeed, textual content maps improve the reading comprehension of deaf students as well (O'Donell and Adenwalla, 1991), so they could be used with the same purpose in SL hypertext. The digital newspaper of the Andalusian Deaf Community (Spain) includes a bilingual content map (text and SL banners) showing the main sections of the newspaper (Fig. 3). The SL banners are activated when the mouse is placed over them, being the static graphic the most representative part of each sign. For more complex hypertext or text content (i.e. scientific hypertext), the content map might not only include the main contents or sections which compose the hypertext system but also a representation of the relationships between sections (e.g. bi-directional or unidirectional links).

As we have reiterated throughout this article, the solutions discussed, extracted from models and data from previous studies conducted with hearing and deaf individuals with textual information, should not be implemented directly without prior empirical testing with deaf signers and SL webs.

In the last two sections, we have mentioned a set of techniques for SL generation which can facilitate information search and learning on the web. However, apart from this functional dimension, there are other aspects that web designers, educators or deaf users need to take into account before making a choice among the systems available. Our precedent review has allowed us to abstract a series of dimensions which configures a taxonomy of techniques for SL generation on the web that is useful in guiding selection. We present it in the following section.

4. Taxonomy of techniques for Sign Language generation on the WWW

After reviewing the literature regarding SL generation, the following dimensions have been revealed as being sufficiently

relevant to differentiate systems: SL communication modality, signing-space, recording, task, authoring tool support, user-testing and applicability in other devices. Next, we define each dimension of the taxonomy (see a summary of technologies according to this taxonomy in Appendix A).

SL communication modality refers to the way SL is conveyed. We have identified at least two modalities: written notation (transcription) and signed communication (Human Signer or Avatar Signer).

- Written notation of gestures: as we mentioned earlier, there are some widely accepted notation systems, such as the Stokoe Notation (Stokoe, 1960) for American Sign Language, the Hamburg Notation System, HamNoSys (Prillwitz et al., 1989) or SignWriting (Sutton, 1977). Advanced SL generators often use them as intermediate representation of real signs; for example, the SiGML notation system used in the eSign project is based on HamNoSys (Kennaway et al., 2007). One of the main drawbacks of notation systems is that their use is not generalized.
- Signed communication by human signers: consist of human signers who are pre-recorded and later displayed on web pages by downloading or streaming videos. Expert and native signers are generally the agents in the videos, so the SL should be effectively articulated. The reliability of SL transmission is high. However, it requires broadband Internet access. In addition, video creation can be highly expensive considering that web pages are regularly updated. As far as implementation and deployment are concerned, on-the-fly video broadcasting requires non-trivial architectures in order to provide, for instance, video streaming.
- Signed communication by avatar signers: the above-mentioned drawbacks caused by the use of human signers (Kennaway et al., 2007) make it more efficient to provide mark-up that will subsequently be translated into a signing avatar. In other words, this modality has the potential to generate SL on demand and for as long as animations are rendered on the users' computer. However, realism, expressiveness and readability are diminished. In addition, note that the plug-ins that transform mark-up into animations are dependent on browsers and their respective release versions. Thus, if the goal is to reach a broad audience it will also require more financial investment. When it comes to virtual avatars, they have some intrinsic characteristics:

Avatar type: if the objective of the avatar is to imitate a human signer it is called a realistic avatar. Old developments that resemble robots are called humanoids. For example, the above-mentioned ViSiCAST and the system developed by Huenerfauth (2008) use humanoids. However, for certain specific purposes, such as SL learning for children, cartoons can be used (Yanagimoto, 2004).

Dimensionality: this refers to the spatial dimensions of avatars as virtual avatars can be 3D or 2D. Hand-shape recognition is a key task in order to convey information accurately and only 3D avatars can provide a complete picture as 2D avatars tend to hide key information such as hand shape, palm orientation, location and movement.

Location rendering: this characterizes the location (server-side or client-side) where the processing of the avatar takes place. Generally, human signing videos embedded in web pages are broadcast on the Internet in the same way as some virtual avatars' animations are; that is, the pre-recorded videos (of human or avatar signers) are placed on the server-side. However, some novel technologies allow the downloading of scripts or mark-up documents that browser plug-ins transform into avatars. This dimension has implications on the resources used as mark-up requires less bandwidth than video content, and browser plug-ins interpret this content dynamically on the client-side.

Technology: avatars for the web can be developed using several technologies such as programming languages (VRML), graphics libraries (DirectX or OpenGL), mark-up (X3D) or by following abstract representations (H-ANIM). However, as mentioned above, some of these solutions, such as X3D-based ones, require browser-dependent plug-ins development, which may cause audience segmentation, and due to financial considerations they only work with one browser.

Some other dimensions to be considered for both human and avatar signers are the following:

Task: this refers to the functionalities offered or the interaction task that the SL generation system provides signer users with. Cunliffe and Herring (2005) distinguish between the use of language for consumption (e.g. reading web sites) and for production (e.g. writing messaging) in multimedia systems and on the web.

Regarding consumption, SL generation systems should allow signer users to efficiently and accurately perform at least two of the most relevant and investigated web tasks such as Information Search (Brumby and Howes, 2008; Kitajima et al., 2000; Pirolli and Fu, 2003; Pirolli, 2004), and Learning (Foltz, 1996; Rouet and Levonen, 1996; Salmerón et al., 2005; Spiro and Jenhg, 1990) which have been the focus of our previous sections. Although some authors distinguish between web searching (looking for a known piece of information) and web browsing (looking around to see what is available), in this paper, we have used the term "search" in a broader sense, which encompasses both task subtypes. According to Jul and Furnas (1997), two search tactics can be followed: queries and navigation, each one having different implications for SL generation systems. Making queries implies SL generation from text to SL or SL to text while navigation implies SL translation of textual hyperlinks or generation of new mechanisms of navigation in SL.

Signer users' learning or knowledge acquisition on the web requires that SL generation systems generate bilingual or SL-only hypertext and hypermedia.

Finally, production happens when users produce SL to communicate with a computer or other remote users (SignWriting messaging by means of notation systems or signed communication, recognized and interpreted by automatic SL recognition systems). The production task is outside the scope of our paper, so we refer to it just to make readers aware of its existence.

Summing up, a SL generation system must allow users to perform four tasks which imply the following challenges:

- *Web search by using queries*: SL generation from written words or SL.
- *Web search by navigation*: SL generation from hyperlinks and hypertext.
- *Learning*: SL generation from hypertext and hypermedia.
- *Communication*: SignWriting messaging

Recording: this dimension characterizes whether SL generation is created on-the fly or needs to be recorded in advance. Pre-recorded content does not only apply to video but also to the development of mark-up that will be later transformed into a SL interpreter. Regarding the dynamic creation of SL, Kennaway et al. (2007) state that automatic translation from written text to SL cannot be achieved in the near future and it should be considered as challenging as translating web pages from one written language to another. As we have seen, in order to address this issue some authors such as Huenerfauth (2008) provide novel solutions which consider Classifier Predicates, one of the more demanding SL elements to be conveyed.

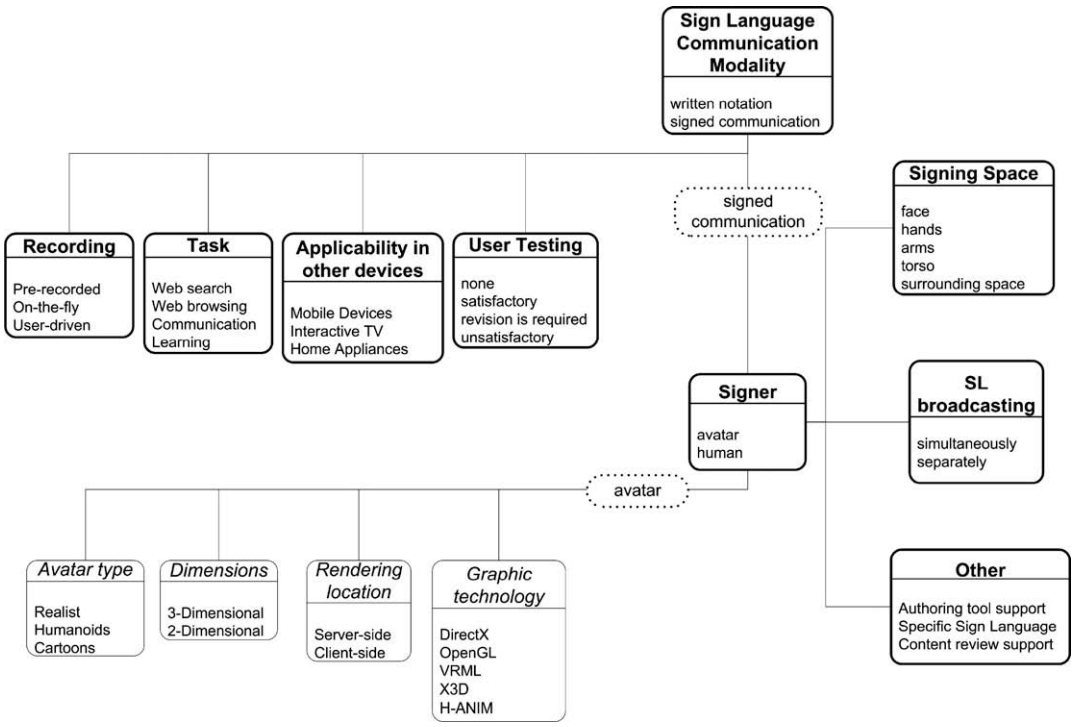

Fig. 6. Taxonomy for SL generation on the WWW.

Applicability in other devices: with the advent of the mobile and ubiquitous web, mobile devices, interactive TV and home appliances can also embed web browsers as the increase in computing performance allows these devices to handle more demanding technologies such as scripting or video support. PDAs or mobile phones have several physical limitations due to their small size. Note that the limited screen size of these devices constrains the readability of SL as information conveyed by face expressions and hands is more difficult to perceive. Some authors have partially addressed mobile communication, proposing a system for mobile messaging making use of SignWritting notation (Ahmed and Kuen Seong, 2006).

User-testing: computer systems involving user interaction should have comprehensive user-testing. This is a Boolean dimension: existent versus non-existent. In the table, user-testing comments are described more accurately.

The following dimensions just impact on signed communication:

Signing-space: most approaches show a whole body or waist-up signer (whether be avatar or human), but in the case of virtual avatars some approaches are incomplete. It is necessary to generate facial expression, hand position, orientation, shape and movement, and body posture for a holistic sign generation, in order to adequately convey SL. Some avatars lack the facial expression (Buttussi et al., 2007), while others lack body motion (Adamo-Villani and Beni, 2005). Only a few approaches consider that the surrounding space can be used for communicative purposes (Huenerfauth, 2008).

SL broadcasting: SL generation can be divided into two modalities depending on the visibility of the information sources. Simultaneous translation from hypermedia (text, video or sound) to SL entails that video is embedded into the web document and both information sources are shown at the same time. Alternatively, translation can be broadcast separately, for example, *via* pop-ups.

Authoring tool support: one of the key factors for a SL generating system to be successful and widely adopted is the authoring tool support, without which developers cannot develop SL content. The purpose of authoring tools can range from creating a mark-up language for avatars to generating hyperlinks for videos of human signers or including subtitles.

Other: the specific SL (e.g. Italian, Spanish, American, etc.) should also be considered as SL generation systems just implement one or at most three SLs while others allow SL corpuses to be created. Finally, providing mechanisms for the user to manipulate SL video reproduction is also extremely helpful. Features such as content preview when the mouse is over the content or content forwarding allows the user to master the SL generation application. Huenerfauth (2009) demonstrated that providing these mechanisms increases user performance in a SL comprehension task and SL animations are better understood. Considering this variable, we have introduced the category "Reviewing Supported" in Table 1. When the user only has limited access to such features (for instance, he is only allowed to pause but not to forward or rewind content), the system is labeled as "limited" in this column. When the systems provide mechanisms for previewing content, understood as an advanced technique for content reviewing, the system is assigned the label "preview".

The Fig. 6 represents how these SL generation characteristics relate to each other in the taxonomy.

Considering the described dimensions, a holistic approach for SL generation on the web should be efficient in terms of implementation, cost and bandwidth. Ideally, SL should be automatically generated and SL representations should be capable of handling hyperlinks. Providing tools for search tasks and other additional features, such as mobile or ubiquity support, will also be extremely significant in the following years. Thus, the challenge will be to provide SL generation with the same features as traditional hypertext at the lowest implementation cost. In addition to such technical requirements, our taxonomy also considers functional dimensions such as the type of web task that technologies might make available: search and learning. The worth of current technologies is assessed according to their functional validity and, when applicable, to the rest of the dimensions in the taxonomy.

5. Conclusions

The digital divide for the Deaf Community partially derives from the low representation of SL in the digital world, which forces signers to navigate in a non-native language. SL generation systems could solve this problem but their validity and usability is not very clear.

This review has shown that in order to enable web information search for signer users, SL cues could be provided in hypertext by means of SL menus or embedding hyperlinks in video clips. Moreover, several notations for SL could be used to implement query systems for SL. However, empirical evidence of the validity of most of the technological approaches does not exist so they should be applied with precaution or pre-tested with the target users beforehand.

With regard to web knowledge acquisition and learning, we have discussed some previous findings indicating that SL may not be as efficient as it can be thought for learning information. This type of finding, together with technical implementation concerns, leads to the conclusion that it might not be either feasible or desirable to use SL-only approaches or to translate all textual content of a website to SL. The brief set of notes proposed in this paper should be taken into consideration for future research about the rational combination of text and signs in hypertext.

On the other hand, the proposed taxonomy helps to categorize SL generation techniques in another set of relevant and interdependent dimensions such as location rendering, SL modality communication, etc. For instance, regarding the modality dimension, we have seen the two main approaches: human signers and avatars. The main advantage of human signers' videos over avatars is that they convey SL more realistically and thus readability is enhanced. However, the weak points are twofold: from the end-user point of view a high-speed Internet connection is required. This entails that the user should have broadband connection coverage and can afford the network connection. From the content providers' point of view, using human signers can be an expensive option and involves using non-conventional client–server architectures.

As a final remark we can state that web designers, web developers, educators or users could take advantage of the proposed taxonomy to critically evaluate and select the technological approach that best fits their needs. We also hope that our review may bring to light for researchers the need to investigate those issues that remain unresolved.

Acknowledgement

Markel Vigo is the recipient of a pre-doctoral fellowship from the Department of Education, Universities and Research of the Basque Government.

Appendix A

Summary of technologies for SL generation on the web according to the dimension of the taxonomy proposed.

System	Communication modality	Main applicable task	Object of transcription	Signing-space	Recording	Authoring tool support	Applicability in other devices	Reviewing supported	Specific Sign Language	Results of user-testing
ViSiCAST Elliott et al. (2000) eSign by Kennaway et al. (2007)	• Avatar • 3D • Realist • Client-side rendering	Web searching: navigation	Text-to-SL	Face, hands, arms, torso	Pre-recorded	Yes	Mobile devices, TV	Yes	British, German and Dutch SL	Improvement in reading comprehension
Francik and Fabian (2002)	• Avatar • 3D • Humanoid	Web searching: navigation	Text-to-SL Speech-to-SL	Hands, arms, torso	On-the fly	N/A	N/A	N/A	Polish	None
Huenerfauth (2008)	• Avatar • 3D • Realist • VRML, DirectX, OpenGL	Web searching: navigation	Text-to-SL	Face, hands, arms, torso and surroundings	On-the-fly	N/A	N/A	N/A	American Sign Language (ASL)	Over performed other systems in grammatically, understandability and naturalness
SigningLink Fels et al. (2006)	• Human	Web searching: navigation	Hyperlink	face, hands, arms, torso	pre-recorded	SignEd	depending on device support	limited	ASL	Satisfactory results but needs revision
Kaibel et al., 2006	• Human	Web searching: navigation	Hyperlink	Face, hands, arms, torso	Pre-recorded	Yes	Depending on device support	Yes	German SL	None
3DictSL Buttussi et al. (2007)	• Avatar • 3D • Realist • X3D and H-Anim	Web searching: querying	Word-to-SL SL-to-word SL-to-SL	Hands, body	User-driven	Yes	Depending on device support	Preview	Italian SL but it is theoretically language independent	None
e-Lis Vettori and Felice (2008)	• Avatar • 2D • Humanoid	Web searching: querying	word-to-SL SL-to-word	Face, hands, arms, torso	User-driven	Yes	Depending on device support	Preview	Italian SL	None
SignWriting in Mobile Phones Ahmed and Kuen Seong (2006)	• Written notation	Communication	text, image and sound	N/A	User-driven	Yes	Mobile devices	Yes	N/A	Satisfactory
Sign Language Subtitling Adamo-Villani and Beni, (2005)	• Avatar • 3D • Realist	Web searching: navigation	video	Semandroid: head and hands	Pre-recorded	Yes	Mobile devices	Yes	ASL	Satisfactory

References

Adamo-Villani, N., Beni, G., 2005. Sign Language Subtitling. ACM SIGGRAPH 2005 Educators program. ACM Press.

Ahmed, A.S., Kuen Seong D.S., 2006. SignWriting on mobile phones for the deaf. In: Proceedings of the 3rd International Conference on Mobile Technology, Applications and Systems, Mobility. ACM Press.

Alegría, J., 1999. La lectura en el niño sordo: elementos para una discusión (Reading in the deaf child: elements for discussion). In: VV. AA. Actes du colloque: Lenguaje Escrito y Sordera. Enfoques teóricos y derivaciones practicas, Publicaciones Universidad Pontificia de Salamanca, Salamanque, pp. 59-76.

Andrews, J.F., Winograd, P., DeVille, G., 1994. Deaf children reading fables: using ASL summaries to improve reading comprehension. American Annals of the Deaf 139, 378–386.

Asensio, M., 1989. Los procesos de lectura en los deficientes auditivos. PhD dissertation. Universidad Autónoma de Madrid.

Banks, J., Gray, C., Fyfe, R., 1990. The written recall of printed stories by severely deaf children. British Journal of Educational Psychology 60, 192–206.

Brumby, D.P., Howes, A., 2008. Strategies for guiding interactive search: an empirical investigation into the consequences of label relevance for assessment and selection. Human–Computer Interaction 23, 1–46.

Buttussi, F., Chittaro, L., Coppo, M., 2007. Using Web3D technologies for visualization and search of signs in an international sign language dictionary. In: Proceedings of the 12th International Conference on 3D Web Technology, Web3D, ACM Press, pp. 61–70.

Caldwell, B., Cooper, M., Guarino Reid, L., Vanderheiden, G., (Eds.), 2008. Web Content Accessibility Guidelines 2.0. W3C Recommendation. <http://www.w3.org/TR/WCAG20/> (accessed 11.11.2008).

Chisholm, W., Vanderheiden, G., Jacobs, I., (Eds.), 1999. Web Content Accessibility Guidelines 1.0. W3C Recommendation. http://www.w3.org/TR/WAI-WEBCONTENT/ (accessed 05.05.99).

Cunliffe, D., Herring, S.C., 2005. Introduction to minority languages, multimedia and the Web. New Review of Multimedia and Hypermedia 11 (2), 131–137.

Dowaliby, F., Lang, H.G., 1999. Adjunct aids in instructional prose: a multimedia study with deaf college students. Journal of Deaf Studies and Deaf Education 4, 270–282.

Elliott, R., Glauert, J.R.W., Kennaway, J.R., Marshall, I., 2000. The development of language processing support for the ViSiCAST project. In: Proceedings of the 4th International ACM Conference on Assistive Technologies, ASSETS 2000, ACM Press, pp. 101–108.

Fajardo, I., Cañas, J.J., Salmerón, L., Abascal, J., 2006. Improving deaf users' accessibility in hypertext information retrieval: are graphical interfaces useful for them? Behaviour & Information Technology 25 (6), 455–467.

Fajardo, I., Arfé, B., Benedetti, P., Altoé, G.M., 2008a. Hyperlink format, categorization abilities and memory span as contributors to deaf users hypertext access. Journal of Deaf Studies and Deaf Education 13 (2), 241–256.

Fajardo, I., Parra, E., Cañas, J.J., Abascal, J., López J.M., 2008b. Web information search in sign language. In: symposium Informal Learning on the Web: Individual Differences and Evaluation Processes, XXIX International Congress of Psychology, pp. 20-25, Berlin, July 2008.

Fajardo, I., Parra, E., Cañas, J.J., Abascal, J., López J.M., Gea, M., 2008c. Web textual hyperlinks supported with sign language videos. In: Workshop on Cognition and the Web 2008, Granada, Spain. 26, April 2008.

Fajardo, I., Cañas, J.J., Salmerón, L., Abascal, J., 2009. Information structure and practice as facilitators of deaf users' navigation in textual websites. Behaviour and Information Technology. Tailor & Francis.

Fels, J., Hardman, J., Lee, D.G., 2006. Sign language Web pages. American Annals of the Deaf 151, 423–433.

Foltz, P.W., 1996. Comprehension, coherence, and strategies in hypertext and linear text. In: Rouet, J.F., Levonen, J.J., Dillon, A., Spiro, R. (Eds.), Hypertext and Cognition. LEA, Mahwah, New Jersey, pp. 109–136.

Francik, J., Fabian, P., 2002. Animating Sign Language in real time. In: 20th IASTED International Multi-Conference, Applied Informatics AI 2002, pp. 276–281.

Garrison, W., Dowaliby, F., Long, G., 1992. Reading comprehension test item difficulty as a function of cognitive processing variables. American Annals of the Deaf 137, 22–30.

Gentry, M.M., Chinn, K.M., Moulton, R.D., 2004–2005. Effectiveness of multimedia reading materials when used with children who are deaf. American Annals of the Deaf 149, 394–402.

Goldin-Meadow, S., Mayberry, R., 2001. How do profoundly deaf children learn to read? Learning Disabilities Research and Practice 16 (4), 222–229.

Huenerfauth, M., 2008. Generating American Sign Language animation: overcoming misconceptions and technical challenges. Universal Access in the Information Society 6 (4), 419–434.

Huenerfauth, M., 2009. A linguistically motivated model for speed and pausing in animations of american sign language. ACM Transactions on Access Computing 2 (2). no. 9.

Huenerfauth, M., Zhao, L., Gu, E., Allbeck, J., 2008. Evaluation of American Sign Language generation by native ASL signers. ACM Transactions on Access Computing 1 (1) (no. 3).

Instituto Estatal de Estadística (Spanish Statistical Office), 2006. <http://www.ine.es/>.

Jul, S., Furnas, G.W., 1997. Navigation in electronic worlds: a CHI 97 Workshop. ACM SIGCHI Bulletin, ACM Press, pp. 44–49.

Kaibel, A. Grote, K., Knoerzer, K, Sieprath, H., Kramer, F., 2006. Hypertext in Sign Language. In: 9th ERCIM "User Interfaces for All" Workshop Adjunct Proceedings. <http://www.ui4all.gr/workshop2006/publications/adjunct-proceedings.html>.

Kintsch, W., 1988. The role of knowledge in discourse comprehension: a construction–integration model. Psychological Review 2 (95), 163–182.

Kintsch, W., 1998. Comprehension: A Paradigm for Cognition. Cambridge University Press, New York.

Kitajima, M., Blackmon, M.H., Polson, P.G.A., 2000. Comprehension-based model of Web navigation and its application to Web usability analysis. In: People and Computers XIV. Springer, pp. 357–373.

Kennaway, J.R., Glauert, J. R.W., Zwitserlood, I., 2007. Providing signed content on the internet by synthesized animation. ACM Transactions on Computer–Human Interaction 14 (3), 1–29.

Kralisch, A., Berendt, B., 2005. Language-sensitive search behaviour and the role of domain knowledge. The New Review of Hypermedia and Multimedia 11 (2), 221–246.

Leybaert, J., Alegria, J., Morais, J., 1982. On automatic reading processes in the deaf. Cahiers de Psychologie Cognitive 2, 185–192.

Marschark, M., Leigh, G., Sapere, P., Burnham, D., Convertino, C., Stinson, M., Knoors, H., Vervloed, M.P.J., Noble, W., 2006. Benefits of sign language interpreting and text alternatives to classroom learning by deaf students. Journal of Deaf Studies and Deaf Education 11, 421–437.

Mautone, P.D., Mayer, R.E., 2007. Cognitive aids for guiding graph comprehension. Journal of Educational Psychology 99, 640–652.

Mayer, R.E., 2005. Principles for reducing extraneous processing in multimedia learning: coherence, signalling, redundancy, spatial contiguity, and temporal contiguity principles. In: Mayer, R.E. (Ed.), The Cambridge Handbook of Multimedia Learning. Cambridge University Press, Cambridge, pp. 183–200.

Michel, T., 2008. W3C Synchronized Multimedia Home Page. <http://www.w3.org/AudioVideo/>.

Moreno, R., Mayer, R.E., 2002. Verbal redundancy in multimedia learning: When reading helps listening. Journal of Educational Psychology 94, 156–163.

Namatame, M., Nishizaki, Y., Kitajima, M., 2007. Improving usability of web pages for hard-of-hearing persons: an investigation of the utility of pictograms. HCI International Posters, 176–180.

Nelson, D.L., Reed, U.S., Walling, J.R., 1976. Picture superiority effect. Journal of Experimental Psychology: Human Learning and Memory 2, 523–528.

O'Donell, A.M., Adenwalla, D., 1991. Using cooperative learning and concepts maps with deaf college students. In: Martin, D.S. (Ed.), Advances in Cognition, Learning and Deafness. Gallaudet University Press, DC, pp. 348–355.

Oakhill, J., Cain, K., 2007. Issues of causality in children's reading comprehension. In: McNamara, D.S. (Ed.), Reading Comprehension Strategies: Theory, Interventions, and Technologies. Lawrence Erlbaum, Mahwah, NJ, pp. 47–72.

Paivio, A., 1991. Dual-coding theory: retrospect and current status. Canadian Journal of Psychology 45, 255–287.

Pirolli, P., Card, S.K., 1999. Information foraging. Psychological Review 106 (4), 643–675.

Pirolli, P., Fu, W.-T.F., 2003. SNIF-ACT: a model of information foraging on the World Wide Web. In: Proceedings of the Ninth International Conference on User Modelling.

Pirolli, P.L., 2004. The use of proximal information scent to forage for distal content on the World Wide Web. In: Kirlik, A. (Ed.), Adaptive Perspectives on Human–Technology Interaction. Oxford University Press, Cambridge UK, pp. 247–266.

Prillwitz, S., Leven, R., Zienert, H., Hanke, T., Henning, J., HamNoSys, 1989. Version 2.0; Hamburg Notation System for Sign Languages. An introductory guide. International Studies on Sign Language and Communication of the Deaf 5, Signum.

Richards, J., Fels, D., Hardman, J., 2005. The Educational Potential of the Signing Web, Instructional Technology and Education of the Deaf.

Rodriguez-Ortiz, I.R., 2007. Sign Language Comprehension: the Case of Spanish Sign Language. Journal of Deaf Studies and Deaf Education Advance Access published December 13, 2007.

Rouet, J.F., Le Bigot, L., 2007. Effects of academic training on metatextual knowledge and hypertext navigation. Metacognition and Learning 2 (2–3), 157–168.

Rouet, J.F., Levonen, J.L., 1996. Studying and learning with hypertext: empirical studies and their implications. In: Rouet, J.F., Levonen, J.L., Dillon, A., Spiro, R.J. (Eds.), Hypertext and Cognition. Erlbaum, Hillsdale, NJ.

Salmerón, L., Baccino, T., Cañas, J.J., Madrid, R.I., Fajardo, I., in press. Do graphical overviews facilitate or hinder comprehension in hypertext? Computers & Education.

Salmerón, L., Cañas, J.J., Kintsch, W., Fajardo, I., 2005. Reading strategies and hypertext comprehension. Discourse Processes 40, 171–191.

Smith, C.E., 2006. Where is it? How deaf adolescents complete fact-based internet search tasks. American Annals of the Deaf 5, 519–529.

Spiro, R., Jenhg, C., 1990. Cognitive flexibility and hypertext: theory and technology for the nonlinear multidimensional traversal of complex subject matter. In: Nix, D., Spiro, R. (Eds.), Cognition, Education and Multimedia: Exploring ideas in High-Technology. Lawrence Erlbaum Associates, Hillsdale, NJ, pp. 163–205.

Stokoe, W., 1960. Sign Language structure: an outline of the visual communication systems of the American deaf. Studies in Linguistics, Occasional Papers, 8.

Sutton, V., 1977. Sutton movement shorthand; writing tool for research. In: Stokoe (Ed.), Proceedings of the 1st National Symposium on Sign Language Research and Teaching. National Association of the deaf, Silver Spring, MD, pp. 267–296.

Sweller, J., 2005. The redundancy principle in multimedia learning. In: Mayer, R.E. (Ed.), The Cambridge Handbook of Multimedia Learning. Cambridge University Press, Cambridge, pp. 183–200 (159–167).
Van Dijk, T.A., Kintsch, W., 1983. Strategies of Discourse Comprehension. Academic Press, Nueva York.
Vettori, C., Felice, M., 2008. e-LIS: ELECTRONIC Bilingual Dictionary Italian Sign Language-Italian. In: Proceedings of the XIII EURALEX International Congress.
Videotext.web. Austrian Sign Language Service Centre and indeed! <http://www.oegsbarrierefrei.at/< <http://www.indeed.at/web/products/>.
World Health Organization (WHO), 2006. Deafness and hearing impairment. <http://www.who.int/mediacentre/factsheets/fs300/en/index.html>.
Yanagimoto, M., 2004. Sign Language Animation Site "Hello! Astroboy". ACM SIGGRAPH 2004. ACM Press.