Holt, R., Bruggeman, L., & Demuth, K. (2021). Children with hearing loss can predict during sentence processing. *Cognition*, 212, 104684.

which has been published in final form at:
https://doi.org/10.1016/j.cognition.2021.104684

Children with hearing loss can predict during sentence processing

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Word count: 3000

ABSTRACT

Listeners readily anticipate upcoming sentence constituents, however little is known about prediction when the input is suboptimal, such as for children with hearing loss (HL). Here we examined whether children with hearing aids and/or cochlear implants use semantic context to predict upcoming spoken sentence completions. We expected reduced prediction among children with HL, but found they were able to predict similarly to children with normal hearing. This suggests prediction is robust even when input quality is chronically suboptimal, and is compatible with the idea that recent advances in the management of pre-lingual HL may have minimised some of the language processing differences between children with and without HL.

KEYWORDS

semantic context, prediction, children, hearing loss, visual world paradigm

1. INTRODUCTION

Listeners readily use contextual information when processing speech. For example, they may employ semantic context to generate predictions about upcoming sentence constituents (e.g., Altmann & Kamide, 1999). Prediction is enabled when the sentence context is constraining: For instance, in *"The boy flies the kite"*, the sentence context (*"The boy flies the…"*) constrains its possible completions. Assuming the sentence is congruent, the object noun must be something which flies, and can be flown by a boy: most likely a kite. In contrast, *"The boy sees the kite"* is unconstraining: The sentence context (*"The boy sees the…"*) does not narrow the range of possible completions, and does not allow prediction to occur.

Prediction can facilitate language processing in several ways. Speech perception *accuracy* may improve as less acoustic information is required before a constituent reaches the threshold for identification (e.g., Conway et al., 2014; Stelmachowicz et al., 2000). Furthermore, language processing may be *faster* as predicted sentence constituents are activated earlier (e.g., DeLong et al., 2005; Dikker & Pylkkänen, 2013; Szewczyk & Schriefers, 2018), and the *effort* required for processing may be reduced for constraining relative to unconstraining sentences (e.g., Winn, 2016; Winn & Moore, 2018). However, there is also a processing cost associated with prediction (Kuperberg & Jaeger, 2016): listeners must expend cognitive capacity to generate and maintain competing possibilities and to reanalyse when predictions are incorrect (Van Petten & Luka, 2012). Limitations in cognitive skills such as working memory and inhibitory control, as well as age-related cognitive decline, therefore tend to impede prediction (e.g., Federmeier & Kutas, 2005; Federmeier et al., 2002; Huettig & Janse, 2016; Zirnstein et al., 2018).

1.1. PREDICTION IN ADVERSE CONDITIONS

Although listeners frequently face adverse listening conditions, little is known about how suboptimal input affects prediction. It has been proposed that less-accessible input may increase the extent to which listeners, as a compensatory mechanism, rely on prediction (Pickering & Garrod, 2007). However, experimental evidence suggests that listeners may be *less* likely to predict when the input is less informative. For example, listeners presented with sentences containing high rates of phonological reduction rely on prediction less than when presented with sentences containing canonical pronunciations (Brouwer et al., 2013).

Pre-lingual hearing loss (HL) provides a special case of adverse listening conditions. While many children with HL achieve functional speech perception via hearing aids (HAs) or cochlear implants (CIs), the quality of their input remains poor relative to normal hearing (NH). HAs, typically used by children with mild to moderate HL, amplify the acoustic signal to a level which can be perceived by the child's residual hearing. HAs thus preserve many characteristics of the signal, but may introduce distortion through signal-processing algorithms, such as wide-dynamic range compression, noise reduction, and frequency compression (e.g., Souza et al., 2015). CIs, used by those with severe to profound HL, convert acoustic input to electrical pulses used to stimulate the auditory nerve directly. This provides a highly distorted signal, often approximated in the lab by four-channel vocoding (e.g., Eisenberg et al., 2002). Use of these hearing devices may additionally be accompanied by auditory processing abnormalities (e.g., Halliday et al., 2019).

If children with HAs and/or CIs are constantly exposed to degraded auditory input, this may impact their use of prediction, especially given that less-informative input reduces prediction for listeners with NH (Brouwer et al., 2013). No studies have yet investigated prediction among children with HL, however some have examined other aspects of semantic context use, finding that primary-school children with HL generally benefit from context less than those with NH. Children with HAs can use semantic context to facilitate word identification in a time-gated word recognition paradigm (Lewis et al., 2017), however they show a more protracted developmental time-course than their NH peers (Walker et al., 2019).

Children with CIs show either no significant improvement in word recognition accuracy when constraining sentence context is available (Conway et al., 2014; Eisenberg et al., 2002), or an improvement in accuracy smaller than that of their NH peers and only for clear, rather than conversational, speech (Smiljanic & Sladen, 2013). Children with HL who do not use a hearing device also show no context-related improvement in accuracy (Stelmachowicz et al., 2000). However, older (adolescent) CI users benefit from context to the same extent as their NH peers in a phoneme monitoring task (Holt et al., 2016), suggesting that the ability to use contextual information may improve with age and CI experience.

Given their limited ability to use contextual information, we expected that primary-school children with HL might struggle to predict. Their slow and effortful language processing may also contribute to reduced prediction. Since children and adolescents with HL tend to process speech more slowly than their NH peers (Burkholder & Pisoni, 2003; Holt et al., 2016; Pisoni et al., 2011), they may not have time to generate predictions about upcoming sentence constituents before they arrive. This is also seen among adults with NH, as listeners with slower processing speeds tend to predict less (Huettig & Janse, 2016). Children with HL may furthermore expend greater cognitive effort on language processing than their NH peers (Hicks & Tharpe, 2002; McGarrigle et al., 2019; though see, e.g., Hughes & Galvin, 2013; Lewis et al., 2016; McFadden & Pittman, 2008). If processing is already more effortful, the benefits of prediction may not outweigh the cognitive cost of generating predictions, or recovering from incorrect predictions (Van Petten & Luka, 2012), providing a disincentive for listeners with HL to predict.

However, children with HL are notoriously heterogeneous, so they may vary in the degree to which they predict. Firstly, children with HAs may behave more similarly to NH peers than children with CIs do, and predict more. Secondly, given the benefits of early intervention for subsequent language development (e.g. Ching et al., 2017; Sininger et al., 2010), children who receive hearing devices earlier may predict more than those who receive devices later. Thirdly, for NH children and adults, prediction ability increases with increasing vocabulary size (Borovsky et al., 2012; Mani & Huettig, 2012) and, among adults, increasing working memory capacity (Huettig & Janse, 2016), so similar patterns may occur for children with HL.

1.2. THE CURRENT STUDY

In this study, we investigated whether children with pre-lingual HL can use semantic context to predict during auditory sentence processing, and whether they do so to the same extent as children with NH. Theoretically, this study contributes to our understanding of the role of context during sentence processing under restricted input conditions. Clinically, it may suggest avenues for future prediction-based interventions for children with HL aimed at improving their language processing speed and reducing effort.

We investigated prediction using the visual world paradigm (Tanenhaus et al., 1995). Participants' looks toward images on the computer screen were recorded while they listened to auditory stimuli. Looks were taken to reflect the lexical candidates listeners considered during spoken-language processing. We compared the timing of looks to images of target nouns presented in sentences with semantically constraining vs. unconstraining contexts. Faster looks to the target image in the constraining than the unconstraining condition indicate prediction. We expected that children with HL would predict less than children with NH, and that prediction would be facilitated by HA (rather than CI) use, earlier device receipt, greater vocabulary size and greater working memory capacity. We also expected that children with HL would look to the target more slowly than children with NH overall.

2. METHODS

2.1. PARTICIPANTS

Children with and without HL participated in the study. The HL group consisted of twenty-five 8-12-year-olds (M_{age}=10;2, *SD*=1;4; 16M, 9F; Table 1). Twenty-two had bilateral HL (bilateral HAs [n=11], bilateral CIs [n=9] or bimodal devices [one HA and one CI; n=2]). The remaining three children had unilateral HL and were HA users. All had sensorineural HL bar one, who had conductive HL due to atresia. Participants with HL included all children who responded to our advertisements; inclusion was not based on performance criteria. Twenty-five 7-12-year-olds with a parental report of NH (M_{age}=9;6; *SD*=1;7; 14M, 11F) formed the control group. All participants had English as their only spoken language and none had any reported cognitive, language or uncorrected vision impairment.

2.2. STIMULI

Thirty-two pairs of sentences of the form "The [agent] [verb] the [target]" were created. Sentences in each pair shared a target word but differed in preceding sentence context: one was constraining and one unconstraining, e.g., "The squirrel climbs the tree" (constraining) vs. "The uncle likes the tree" (unconstraining). Sentences were recorded by a female native speaker of Australian English. To facilitate time-locking of looking behaviour, the duration of each sentence constituent was normalised to the mean duration of that constituent across all sentences (Borovsky et al., 2012; Table 2) using Praat (Boersma & Weenink, 2019).

***Table 1 – Characteristics of participants with hearing loss**. Arranged by increasing bilateral four-frequency pure tone average (PTA). When not available for each ear separately, only a bilateral PTA is provided. When only individual ear PTAs were provided, bilateral PTA was calculated as the average value across the two ears. Abbreviations: M = male; F = female; HA = hearing aid; BAHA = bone-anchored hearing aid; BSL = British Sign Language; CROS = contralateral routing of signals hearing aid; CI = cochlear implant; LVAS = large vestibular aqueduct syndrome*

Age (years; months)	Gender	Current device type(s)	Laterality of HL	Four-frequency pure tone average HL – left ear (dB)	Four-frequency pure tone average HL – right ear (dB)	Four-frequency pure tone average HL – bilateral (dB)	Age at HA fitting (years; months)	Age at first CI switch-on (years; months)	Duration of device use (years; months)	Aetiology	Exposure to languages other than English
9;8	F	HAs	Bilateral	15	23	19	4;2	*Not applicable*	5;6	*Unknown*	5% Greek
12;8	F	HAs	Bilateral	33	28	31	10;8	*Not applicable*	2;0	*Unknown*	None
9;6	M	BAHA	Unilateral (left)	58	10	34	0;3	*Not applicable*	9;3	Atresia	None
9;7	M	HA	Unilateral (right)	5	74	40	0;2	*Not applicable*	9;5	*Unknown*	None
9;10	M	HAs	Bilateral	43	42	43	0;2	*Not applicable*	9;8	Connexin-26	None
9;4	M	HAs	Bilateral	*Unavailable*	*Unavailable*	45	0;6	*Not applicable*	8;10	*Unknown*	None
8;9	M	HAs	Bilateral	49	46	48	0;1	*Not applicable*	8;8	OTOA gene	10% Auslan
9;3	M	HAs	Bilateral	50	51	51	0;10	*Not applicable*	8;5	*Unknown*	None
12;9	F	HAs	Bilateral	50	51	51	3;4	*Not applicable*	9;5	*Unknown*	None
9;3	M	HAs	Bilateral	58	55	57	4;6	*Not applicable*	4;9	Genetic	None
10;1	F	HAs	Bilateral	54	59	57	0;1	*Not applicable*	10;0	OTOA gene	10% Auslan
9;3	F	HAs	Bilateral	*Approx. 58*	*Approx. 58*	*Approx. 58*	*Unavailable*	*Not applicable*	*Unavailable*	Genetic	5% Auslan
9;6	M	CROS	Unilateral (left)	120	5	63	0;4	*Not applicable*	9;2	*Unknown*	None
9;3	F	CI/HA	Bilateral	96	44	70	0;1	2;11	9;2	Connexin-26	15% BSL
8;8	F	CI/HA	Bilateral	108	35	72	3;10	4;6	4;10	LVAS	None
8;10	F	CIs	Bilateral	69	89	79	0;2	3;0	8;8	LVAS	<5% Auslan
11;4	M	HAs	Bilateral	89	88	89	6;6	*Not applicable*	4;10	Genetic	None
10;1	M	CIs	Bilateral	80	100	90	1;9	2;4	8;4	*Unknown*	None
11;1	F	CIs	Bilateral	*Unavailable*	*Unavailable*	95	0;1	0;9	11;0	*Unknown*	10% Bosnian
8;8	M	CIs	Bilateral	110	83	97	*Unavailable*	2;11	*Unavailable*	Cytomegalovirus	30% Auslan
10;11	M	CIs	Bilateral	*Unavailable*	*Unavailable*	102	*Not applicable*	1;2	9;9	Meningitis	None
11;2	M	CIs	Bilateral	*Unavailable*	*Unavailable*	105	0;3	1;7	10;11	*Unknown*	None
12;5	M	CIs	Bilateral	95	120	108	5;2	7;0	7;3	*Unknown*	None
10;8	M	CIs	Bilateral	*Unavailable*	*Unavailable*	120	0;1	1;6	10;7	*Unknown*	None
12;6	M	CIs	Bilateral	120	120	120	0;2	0;7	12;4	Waardenburg syndrome	None

Table 2 – Durations of stimulus sentence constituents following normalisation.

Sentence constituent	**Normalised duration (ms)**
The	139
Agent	761
Verb	809
The	121
Target	990
TOTAL	*2820*

An array of four images forming the 'visual world' was constructed for each sentence pair. One image represented the target (e.g., a tree, in the above example), and the others different types of distractors (Borovsky et al., 2012; Figure 1). See Supplementary Material 1 for details of stimuli preparation and validation.

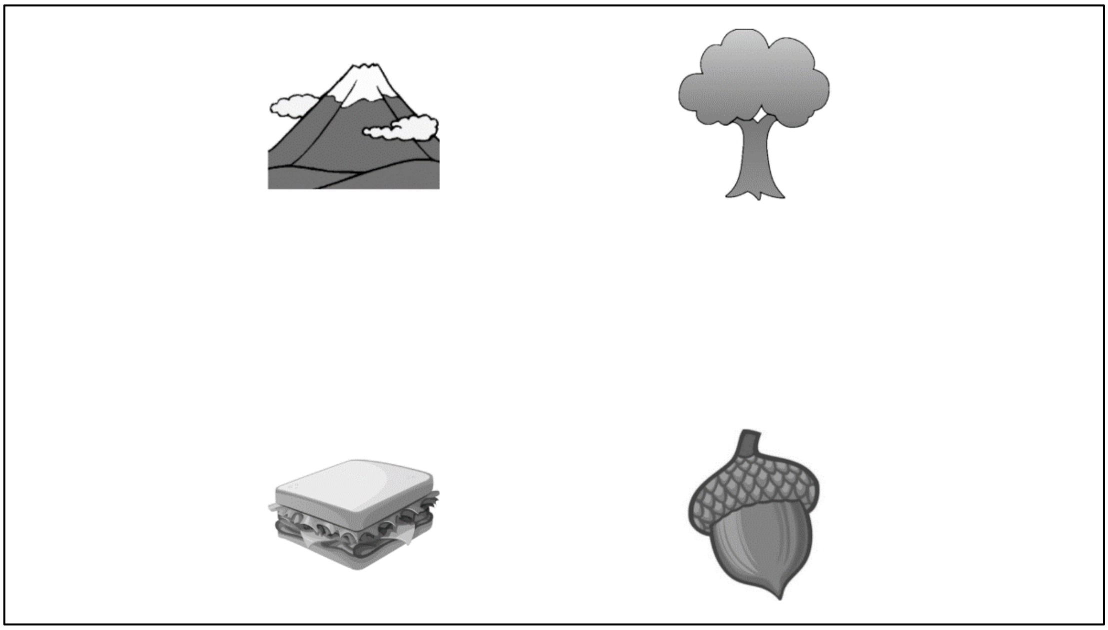

Figure 1 – Sample image array used in the eye-tracking task.

2.3. PROCEDURE

The eye-tracking task took approximately 10 minutes, forming part of a one-hour testing session. It was presented on an Alienware 15 R3 laptop via Tobii Pro Lab software (Tobii Pro AB, Stockholm, Sweden). Gaze direction was recorded at 60 Hz with a Tobii X2-60 portable eye-tracker. Audio was presented at a mean intensity of 60 dB SPL via a Soundblaster X7 external soundcard and a Genelec 8020C active monitor. After eye-tracker calibration, three practice trials and 32 test trials (one sentence from each pair; half constraining, half unconstraining) were completed. For each trial, the image array was presented for 2000 ms. Then, while the array remained on screen, the corresponding sentence played. After a further 2000 ms, the image array background colour changed from white to blue and the mouse cursor appeared on the screen. This was participants' cue to click on the image that best matched the sentence.

3. ANALYSIS AND RESULTS

Trials were excluded if participants had not correctly clicked on the target image (n_{NH}=8; n_{HL}=33) or if the trial contained 1000 ms or longer of consecutive track loss (n_{NH}=62; n_{HL}=60; Koring et al., 2017). Thus, 163 trials out of 1600 were rejected (10%). Areas of interest (AOIs) were defined as the regions occupied by each 300x300 pixel image, plus 40 pixels on each side. After manual drift correction, the proportion of looks to each AOI in constraining and unconstraining conditions was calculated for each participant at each sampling point. Figure 2 shows these proportions with time in milliseconds. All analyses, however, were conducted with time quantified in samples.

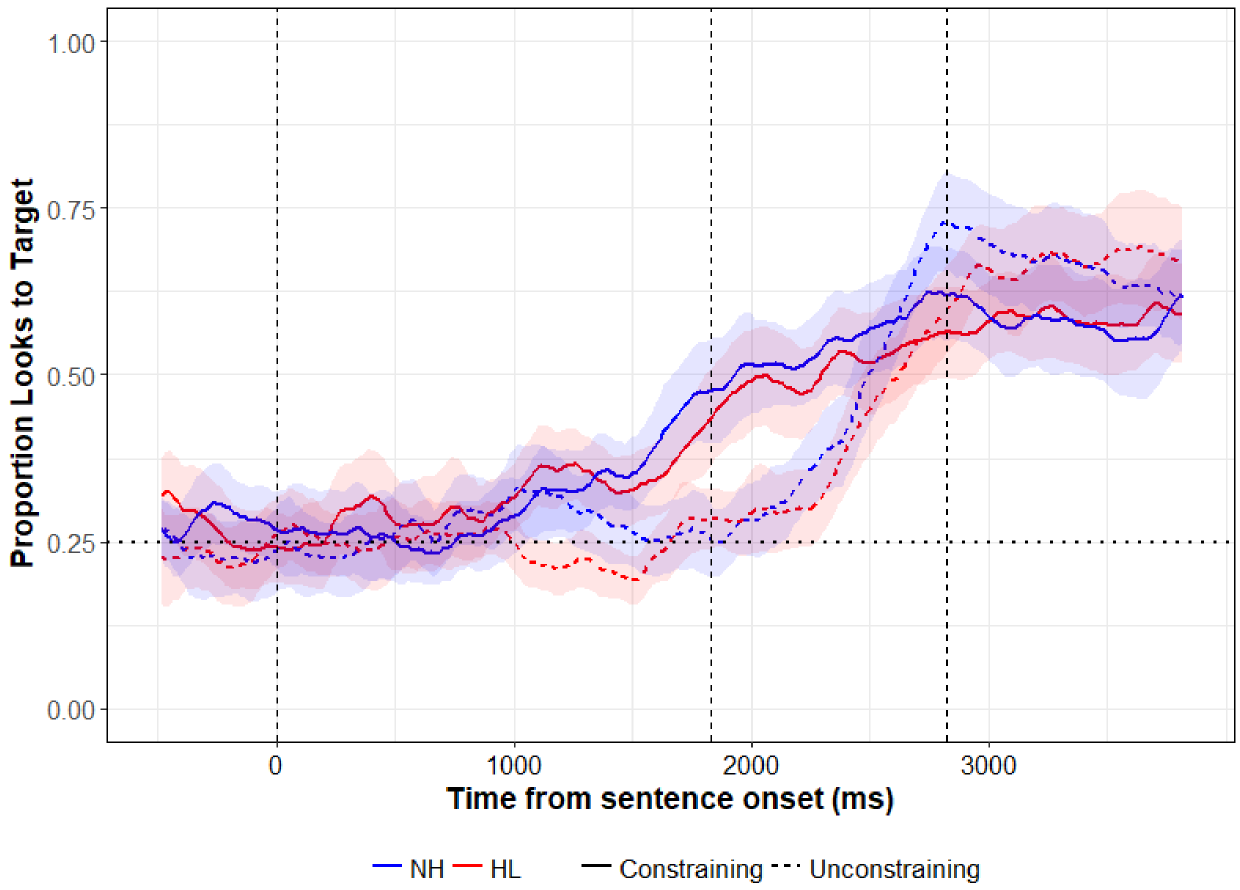

Figure 2 – Mean proportion of looks to target image across trial. *NH (blue) and HL (red) groups in constraining (solid line) and unconstraining (dashed line) contexts. Shaded areas show 95% confidence interval of the mean. Horizontal dotted line shows chance. Vertical dashed lines show sentence onset (0 ms), target word onset (1830 ms) and sentence offset (2820 ms).*

As data from individual participants were noisy due to the relatively small number of trials, jackknifing was used to provide a transformation of the data that could be accurately fit with a logistic curve (cf. Apfelbaum et al., 2011; Galle et al., 2019). Jackknifing involves subtracting each participants' data for a certain condition from the mean for their group in that condition (Ulrich & Miller, 2001). The resulting proportions of looks to the target capture the behaviour of individual participants by showing mean looking behaviour when that participant is *removed*, and, due to the larger amount of data included (in this case, observations from 24 participants vs. one participant), providing smoother curves which can be fit more accurately.

A four-parameter logistic curve was fit to each participant's jackknifed looks to the target in each condition using McMurray's (2020) non-linear curvefitter (all $r \geq .98$). The parameter of interest was the crossover point (the point at which the curvature shifts from negative to positive or vice versa), with an earlier crossover signifying earlier looks to the target (cf. Apfelbaum et al., 2011). Crossover point values were extracted from the jackknifed data and used to calculate estimates of each participant's actual (non-jackknifed) crossover point (cf. Smulders, 2010; Figure 3).

Estimated crossover points were analysed with a linear mixed-effects model in R (R Core Team, 2018), using lme4 (Bates et al., 2015). The model included the fixed factors Constraint (constraining vs. unconstraining contexts) and Group (HL vs. NH) and a random intercept for Participant. After model fitting, three outliers were removed (observations with residuals more than 2.5 standard deviations from the mean [Baayen & Milin, 2010]; no participant had both observations excluded). The model was then re-fit and tested for significance. Only a significant effect of Constraint was found (β=23.28, SE=3.40, p<.001; Table 3). To confirm that the effect of Constraint was present for both participant groups, separate models were constructed by group. In both cases, the crossover point occurred significantly earlier in the constraining condition (NH: β=24.96, SE=4.53, p<.001; HL: β=23.54, SE=4.54, p<.001).

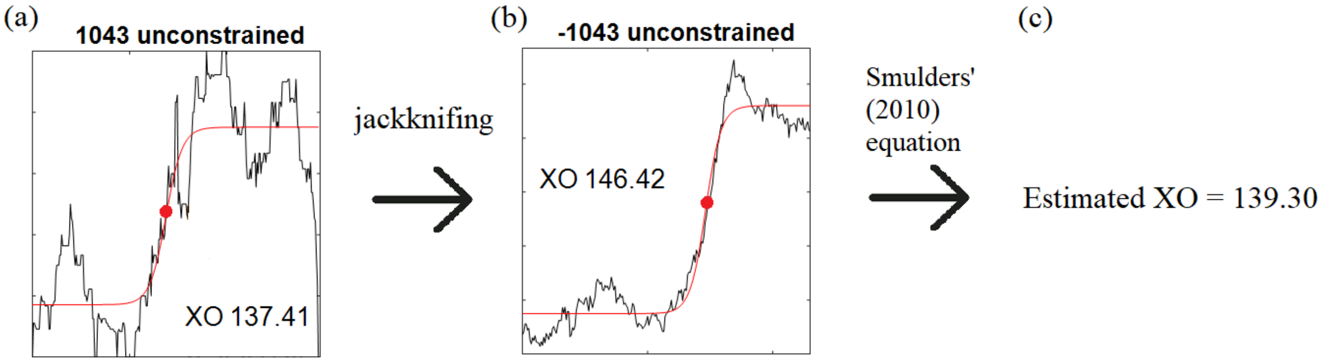

Figure 3 – Schematic of the data analysis procedure. *Real data from participant '1043' in the unconstraining condition. Screenshots from McMurray's (2020) curvefitter. Crossover point location (XO) measured in samples from the sentence onset. Approximate locations of the crossover point shown as red dots. (a) Noisy raw data (in black) leads to a suboptimal curve-fit (in red,* r = *.89 in this example). (b) Jackknifed data provides a more accurate curve-fit (*r = *.98 in this example). (c) Equation (Smulders, 2010) used to calculate estimate of participant's actual crossover point based on the jackknifed value.*

Table 3 –* lmer *output for confirmatory analysis. *Estimates and standard errors are measured in sampling points: One sample equates to 16.67 ms.*

Factor	**Estimate**	**Standard error**	***p*-value**
Intercept	125.95	3.51	< .001
Sentence constraint	23.28	3.40	< .001
Group	-2.78	3.51	.43
Sentence constraint * Group	-0.32	3.40	.93

Exploratory analyses did not find any significant relationships between participant characteristics (vocabulary size, working memory capacity, hearing device type, age at first device) and the extent of individuals' prediction (see Supplementary Material 2), and so will not be discussed further.

4. DISCUSSION

This study aimed to determine whether children with HL can use prediction in auditory sentence processing, similar to their NH peers. Although we hypothesised that they would show reduced or absent prediction, children with HL did indeed utilise prediction, as shown by their significantly earlier looks to the target image in constraining than unconstraining contexts, and did so no differently to their NH peers. We also found no evidence that children with HL processed language any slower than their peers with NH overall (the model estimate of the [non-significant] timing difference between the average crossover points of the two groups was only 46 ms; Table 3).

These results contrast with those of previous studies finding no use of context (Conway et al., 2014; Eisenberg et al., 2002; Stelmachowicz et al., 2000) and slow language processing (Burkholder & Pisoni, 2003; Pisoni et al., 2011; Holt et al., 2016) among children with HL. We suggest that these differences may be related to the intervention and technologies available to participants. In earlier studies, most participants with bilateral HL either used a unilateral CI, or no hearing device at all. Some CI users were implanted very late compared to those in the current study, with the mean age at implantation in some studies as high as 5;2 (Table 4). In contrast, all of our participants used bilateral devices if their HL was bilateral, and CI users with non-progressive HL were implanted by age 1;5 on average. It is thus not surprising that CI users in our study, who generally received a high standard of early intervention, would behave more similarly to children with NH. Additionally, as hearing device technology has rapidly advanced over the past few decades, the newer devices available to our participants (received around the early 2010s) may have contributed to their more NH-like performance.

Table 4 – Summary of prior studies finding differences between children with and without HL in use of semantic context or language processing speed.

Study	**Topic**	**Mean age at testing (years; months)**	**HL laterality and severity**	**Device configuration**	**Mean age at implantation (years; months)**	**Estimated time of device receipt**
Stelmachowicz et al., 2000	Context	Approx. 8;8	Bilateral mild to moderate-severe HL	No device(s)	N/A	N/A
Eisenberg et al., 2002	Context	8;7	Bilateral severe-profound to profound HL	Primarily unilateral CI (25% used a contralateral HA)	5;2	Mid- to late-1990s
Smiljanic & Sladen, 2013	Context	8;6	Bilateral profound HL	Primarily unilateral CI (33% used a second CI)	2;3	Early- to mid-2000s
Conway et al., 2014	Context	7;6	Bilateral profound HL	Primarily unilateral CI (12.5% used a second CI or a contralateral HA)	1;9	Mid-2000s
Holt et al., 2016	Context & processing speed	16;2	Bilateral profound HL	Primarily unilateral CI (25% used a second CI)	1;10	Early-2000s

Burkholder & Pisoni, 2003	Processing speed	8;8	Bilateral profound HL	Unilateral CI	3;1	Late-1990s
Pisoni et al., 2011	Processing speed	Approx. 9;0	Bilateral profound HL	Unilateral CI	3;5	Early- to mid-1990s

One might attribute the lack of difference between HL and NH groups in the present study to the inclusion of HA users, due to their lesser signal degradation than CI users. However, our results do not support this, as our exploratory analysis found no significant differences in prediction between HA and CI users. The average magnitude of prediction was almost identical, with the crossover point occurring 698 ms earlier in the constraining than the unconstraining context for children with HAs, and 685 ms earlier for children with CIs.

An additional factor which may contribute to the lack of difference in *processing speed* between children with and without HL is task difficulty. Studies finding slower language processing among children with HL than NH have employed relatively difficult tasks: phoneme monitoring, which relies on phonological awareness (Holt et al., 2016); and a sentence repetition task, which taxes working memory (Burkholder & Pisoni, 2003; Pisoni et al., 2011). In contrast, the current study simply required participants to comprehend sentences. It may be that reduced cognitive demand enables children with HL to process language just as rapidly as children with NH, whereas more difficult tasks may disproportionately slow them down.

Future research may examine the generalisability of our findings, as differences in prediction between children with and without HL may still exist in more challenging communicative situations or when predictions are generated based on other linguistic phenomena, e.g., syntactic agreement, rather than semantics. It would also be valuable to compare our findings to a context where comprehensive early intervention is not the norm, to confirm whether the NH-like language processing shown by participants in this study is indeed attributable to intervention type and quality.

In sum, we have demonstrated that prediction in language processing is possible even for listeners whose input is chronically suboptimal. Even though less-informative input reduces NH listeners' use of prediction (Brouwer et al., 2013), it does not seem to impede prediction when that quality is what listeners are *used to*. Furthermore, our findings suggest that the children in our study (HA and CI users, who generally received early intervention and therapy according to current best practice in Australia) may achieve language processing more similar to that of their NH peers than children in most previous studies, who received later and more limited access to sound. Finally, as we find no evidence of impaired context use in children with HL, this suggests that listening strategies emphasising the use of contextual information may benefit these children. Context use can improve perception accuracy (e.g., Eisenberg et al., 2002), processing speed (the current study) and reduce processing effort (e.g., Winn, 2016). By better understanding the prediction capabilities of children with HL, we are better equipped to consider possible interventions that may facilitate language processing in this population.

Acknowledgements

We thank Benjamin Davies for assistance with data collection and pre-processing, Colleen Merhi and Sarah Resende for assistance with stimuli preparation and piloting, and Louise Ratko for recording the stimuli. Marcus Ockenden and Craig Richardson provided invaluable technical support. We thank Tracy Hopkins, Tess Ansell and Liz Semkoski (The Shepherd Centre), Greg Leigh and Inge Kaltenbrunn (Royal Institute for Deaf and Blind Children) and Alison King (Hearing Australia) for assistance with participant recruitment and provision of participant details, Amanda Piper, Celeste Rodriguez Louro and Collette Ryan for facilitating interstate data collection, and Isabel O'Keeffe for coordinating with hearing service providers.

Funding: This work was supported by the Australian Research Council [grant number ARC FL130100014]; and Macquarie University [grant number MQ RIS83034101].

Author contributions

Rebecca Holt: Conceptualisation, methodology, investigation, formal analysis, writing – original draft. Laurence Bruggeman: Conceptualisation, methodology, writing – review & editing. Katherine Demuth: Conceptualisation, methodology, supervision, writing – review & editing.

Supplementary material

Raw data for this study can be found online at the Open Science Framework (https://osf.io/dwvuc/, DOI: 10.17605/OSF.IO/DWVUC).

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