Developmental improvements in perceptual restoration: Can young children reconstruct missing sounds in noisy environments?

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Abstract

Young children are frequently exposed to sounds such as speech and music in noisy listening conditions, which have the potential to disrupt their learning. Missing input that is masked by louder sounds can, under the right conditions, be ‘filled in’ by the perceptual system, using a process known as perceptual restoration. This experiment compared the ability of 4- to 6-year old children, 9- to 11-year-old children, and adults to complete a melody identification task using perceptual restoration. Melodies were presented either intact (complete input), with noise-filled gaps (partial input; perceptual restoration can occur) or with silence-filled gaps (partial input; perceptual restoration cannot occur). All age groups could use perceptual restoration to help them interpret partial input, yet perception was the most detrimentally affected by the presentation of partial input for the youngest children. This implies that they might have more difficulty perceiving sounds in noisy environments than older children or adults. Young children had particular difficulty using partial input for identification under conditions where perceptual restoration could not occur. These findings suggest that perceptual restoration is a crucial mechanism in young children, where processes that fill in missing sensory input represent an important part of the way meaning is extracted from a complex sensory world.

The vast majority of our everyday acoustic environments are sufficiently noisy that much of the sensory input we receive can be incomplete. Such environments have the potential to cause serious disruptions to sensory processing, yet meaningful percepts can be formed from incomplete sensory input. Whether young children's perception is more likely to be detrimentally affected in noisy listening conditions than that of older children and adults represents an important concern with clear educational implications.

“Filling in” the content of missing or disrupted sensory input is seen as a general property of sensory systems (e.g. Bremner, Johnson, Slater, Mason, Cheshire & Spring, 2007; Kitagawa, Igarashi & Kashino, 2009). Even as early as 4 months, infants possess the ability to complete occluded gaps in visual stimuli (e.g. Johnson, Bremner, Slater & Mason, 2000; Johnson, Bremner, Slater, Mason & Foster, 2002). Evidence suggests that a similar process occurs in the auditory domain (e.g. Newman, 2004; Warren, 1970). When missing input is masked by noise, the missing sounds can be perceptually recreated to the extent that they are often indistinguishable from sounds actually present (Warren & Warren, 1970). This reconstruction of missing sounds is termed perceptual restoration.

Warren (1970) demonstrated that missing phonemes in a spoken sentence were heard by adult listeners to be present when replaced by a cough (they were ‘perceptually restored’), but not when replaced by a silent gap. In parallel to research in the visual domain, continuity of disrupted signals can only be perceived where clear evidence for occlusion is present (e.g. Bremner et al., 2007). This perceptual restoration effect is believed to result from the combination of top-down contextually-generated expectations of the content of the missing information and bottom-up confirmation of these expectations provided by masking or occluding noise (e.g. Shahin, Bishop & Miller,

2009). The noise that masks or replaces the missing fragment is crucial in preventing detection of discontinuity of the signal, and maintaining its global coherence. This therefore explains why missing sounds can be recreated when replaced or masked by noise, but not when replaced by silence.

In recent years there has been a renewed interest in the perceptual restoration effect, which acknowledges the key ecological value of perceptual restoration in supporting auditory perception in the kinds of noisy environments we are faced with daily (e.g. Husain, Lozito, Ulloa & Horwitz, 2005; Petkov, O'Connor & Sutter, 2007; Riecke, Mendelsohn, Schriener & Formisano, 2009; Shahin et al., 2009). In fact, signal disruptions are so common that restoring missing content is seen as one of the most important tasks that the auditory system in adults must undertake (Remijn, Pérez, Nakajima & Ito, 2008; Seeba, Schwartz & Bee, 2010). Given the importance of perceptual restoration, it is perhaps surprising that less is known about the developmental origins of these abilities. Much of children's learning, both speech- and music-based, takes place in environments that can be noisy (e.g. Mills, 1975). In order for children to gain maximum benefit from learning experiences, it would be beneficial if children, as well as adults, have ways of compensating for disrupted input. Perceptual restoration is a prime example of such a mechanism.

There is some evidence that this perceptual restoration ability operates in young children in the speech domain (Koroleva, Kashina, Sakhnovskaya & Shurgaya, 1991; Koroleva, Shurgaya, Kashina & Sakhnovskaya, 1996; Walley, 1988). Furthermore, there are developmental improvements in the ability to reconstruct missing speech sounds using perceptual restoration, with Ackroff (1981) finding an improvement in the

perceptual restoration of a missing phoneme between the ages of six and eight years.

However, it appears that children are not able to reconstruct missing sounds using perceptual restoration to the same degree as adults (Walley, 1988).

Most recently, Newman (2004) compared the perceptual restoration abilities of adults and 5-year-old children. Multiple alternating fragments of spoken sentences were removed and replaced with either noise or silence, and listeners' repetition accuracy of the sentences was assessed, and compared to their repetition accuracy of intact sentences. If perceptual restoration occurred, listeners would be better able to repeat the sentences where missing sections were replaced by noise, even though the same amount of intact speech was present in both cases. This was indeed what Newman found, for both adults and 5-year-olds. Newman interpreted this finding as evidence of young children's ability to combine their previous stored knowledge with incoming acoustic information in the process of perception. However, young children showed more of a detriment to their repetition of sentences with noise-filled gaps in comparison to intact stimuli, than was the case for adults. Newman interpreted this as evidence that children's perception is more greatly affected by disruptions than that of adults.

Children's difficulty interpreting disrupted input was further demonstrated in a study by Newman (2006) that failed to find evidence of perceptual restoration in 2- to 3-year-old children. So whilst perceptual restoration can provide a comparable advantage relative to silence-filled missing fragments in both adults and 5-year-old children, this does not mean that children's ability to interpret partial input is as good as that of adults.

Taken together, these findings suggest that children might have greater difficulty using context to infer the likely content of missing information than do adults, and as a

result might be more seriously affected by signal disruptions in noisy environments. Newman suggests that the use of previous knowledge in the process of perception in young children differs from that of adults, and that with development comes the ability to make better use of top-down contextual knowledge in the perceptual process. These findings are also consistent with claims that strategies for perceptual processing change throughout lifespan development (Warren & Warren, 1971).

Previous research demonstrates that children as young as five years old can use perceptual restoration yet have more difficulty than adults when interpreting disrupted sensory input. It is not clear, however, whether these findings are specific to speech perception, or represent a more domain-general difficulty. Perceptual restoration does not only work to restore missing content of speech signals; perceptual restoration has also been demonstrated in the music domain. Missing musical notes can be heard as present provided they are masked by noise in both adults (DeWitt & Samuel, 1990; Kaminska & Mayer, 1993; Sasaki, 1980) and 4- to 6-year old children (Winstone, 2009). This suggests that the perceptual restoration mechanism is not restricted to restoring the missing content of speech communication, but might represent a more general property of sensory processing that operates in different auditory domains.

In the present study we examined the ability of 4- to 6-year-old children, 9- to 11-year-old children, and adults to identify familiar melodies using perceptual restoration. These age groups were selected in order to make comparisons with age developments in the perceptual restoration of speech, where young children have been compared with older children (Ackroff, 1981), and young children have been compared with adults (e.g. Newman, 2004). Melodies were either presented intact (complete input), with missing

fragments replaced by noise (partial input; perceptual restoration can occur) or with missing fragments replaced by silence (partial input; perceptual restoration cannot occur). Thus, a comparison between the noise-filled gaps and silence-filled gaps conditions, where exactly the same amount of intact information that could help identification of the melodies is present, can be made. The only difference between noise-filled gaps and silence-filled gaps conditions is the confirmation of expectations provided by the replacement noise. This paradigm is well-established in experimental work on perceptual restoration (e.g. Bashford, Riener & Warren, 1992; Koroleva et al., 1996; Newman, 2004; Powers & Wilcox, 1977). If perceptual restoration operates, we expect to see a significant noise-filled gaps over silence-filled gaps advantage in melody identification, and of key interest are developmental changes in the ability to identify each type of stimulus.

Method

Participants

There were a total of 156 participants, divided into three age groups. The ‘young children’ group consisted of 66 children (27 girls) between the ages of 4 years 7 months and 6 years 8 months, with a mean age of 5 years 9 months ($SD = 7.06$ months). The ‘older children’ group consisted of 60 children (29 girls) between the ages of 9 years 4 months and 11 years 1 month, with a mean age of 10 years 1 month ($SD = 6.76$ months). Both the younger and older children were recruited from two primary schools, one in Surrey, UK and one in Dorset, UK. Both schools were situated in predominantly white, middle-class areas, and all children were native English speakers and were reported by

their school to have normal hearing. Consent for participation was obtained from both the child's parent or guardian and the school Headteacher. The 'adult' group consisted of 30 undergraduate students (27 females) from the University of Surrey, ranging in age from 18 years 3 months to 20 years 11 months, with a mean age of 19 years 6 months ($SD = 9.40$ months). All of the adult participants were native English speakers with normal hearing, and were offered course credit for their participation.

Design

The experiment consisted of a 3×3 independent groups design. Participants in each of the three age groups were randomly allocated to one of three experimental conditions¹ (intact, noise-filled gaps or silence-filled gaps). All participants were presented with the same nursery rhyme melodies for identification, but these were modified according to the experimental condition (see Figure 1). In the intact condition, nursery rhyme melodies were not manipulated. This served as an important control condition giving a measure of optimal performance when no signal disruptions were present. In the noise-filled gaps condition, alternate 100 ms fragments were removed from the melody and replaced with white noise². Finally, in the silence-filled gaps condition the fragments were removed from the melody and were replaced with 100 ms fragments of silence. The duration of missing fragments was set at 100 ms (the shortest duration of interruption presented in Newman's (2004) study). Pilot work had shown that when longer gap durations were presented, identification of stimuli with silence-filled gaps in the youngest participants was near floor level. With an average note duration of

380 ms in the melodies presented, a gap duration of 100 ms ensured that that in no case was an entire note missing from the melody.

Whilst many previous studies in the area of perceptual restoration of speech (e.g. Newman, 2004) employ a within-subjects design, where each participant is presented with intact, noise-filled gaps and silence-filled gaps stimuli, this design was difficult to implement in the present study for the following reasons. Using repetition accuracy of spoken sentences as a dependent measure, as Newman (2004) did with her speech stimuli, does not require stimuli to be familiar to the participant. Thus, a potentially infinite number of stimuli can be generated, making it possible to present a good number of intact, noise and silence stimuli to each participant. Our pilot work showed that repetition accuracy of melodic stimuli was not feasible with young children. Therefore we used recognition accuracy as a dependent measure, requiring each stimulus to be familiar. Pilot work identified 15 nursery rhyme melodies that were familiar to participants, meaning only a few stimuli of each type could be presented in a within-subjects design. This made a between-subjects design more feasible given the nature of the participants, the stimuli, and the dependent measure.

INSERT FIGURE 1 ABOUT HERE

Materials

The 15 stimuli, melodies taken from children's nursery rhymes and play songs³ (see Appendix), were produced using an Oxygen8 MIDI keyboard (M-Audio, Irwindale, CA, USA) with piano sound selected, connected to Garageband v3.0.4 for Macintosh

(Apple Inc., Cupertino, CA, USA). Sound Studio v2.2.4 (Felt Tip Software, Wayne, PA, USA) was used to equate the peak amplitude of the melodies and to replace fragments of 100 ms in duration with white noise (of higher amplitude than the peak amplitude of the signal), or silence. For all noise and silence stimuli there was a strict sequential alternation between 100 ms signal-on and 100 ms signal-off. The cut points were not specifically taken at the zero-crossings, but the cuts are strictly time-linked and no large audible clicks were noticeable. The noise used was random noise (white noise /Johnson noise) with equal energy per frequency. All individual segments of white noise were independent and generated at random.

A programme written in Matlab v5.2.1 (MathWorks, Natick, MA, USA) presented the stimuli (sampling rate 22.25 KHz) in a random order and recorded the participants' responses. The MatLab programme incorporated the psychophysics toolbox SND command (Pelli, 1997); in contrast to the MatLab SOUND command the SND command returns immediately allowing interrupts and thus control over the stimulus presentation. Familiarity with the melodies was established for all age groups through the administration of a song familiarity questionnaire prior to testing sessions⁴.

Procedure

Each participant was tested individually in a quiet room, and was given the following instructions:

“I need your help to work out what some children’s tunes are. They are sounding a bit silly on my computer and I don’t know them very well. Listen to each tune carefully. As soon as you know what the tune is, say ‘stop!’ and you can tell me the name of the tune. You do not need to wait until it has finished playing”

Stimuli were presented over closed-back headphones (Grado SR80s with a flat midrange; Grado Labs, Brooklyn, NY, USA) to prevent any background noise disruption.

Participants were presented with two demonstration trials (always ‘Baa Baa Black Sheep’ and ‘The Grand Old Duke of York’), followed by 13 experimental trials. If the participant did not identify the nursery rhyme from the demonstration trial, no further explanation was given, and the next trial followed immediately. No feedback was given as to whether responses to experimental trials were correct or incorrect. Failure to give a response was coded as incorrect.

Results

Each participant was given a score out of 13 which represented the number of melodies they identified correctly in the experimental trials. There were no gender differences in identification scores for any age group so data were collapsed across gender. Figure 2 shows the mean number of melodies identified correctly by participants in each age group and experimental condition.

INSERT FIGURE 2 ABOUT HERE

These data were analysed using a 3 (Age Group: young children; older children; adults) x 3 (Experimental Condition: intact; noise-filled gaps; silence-filled gaps) between-subjects ANOVA. First, identification scores differed significantly by age

group, $F(2, 147) = 79.78, p < .001, \eta^2_p = .52$. The identification scores of young children ($M = 6.03, SD = 2.48$) were significantly lower than those of older children ($M = 8.18, SD = 1.65$; Tukey HSD $p < .001, d = 0.87$) and adults ($M = 9.23, SD = 2.13$; Tukey HSD $p < .001, d = 1.29$). In addition, there was also a significant difference between the identification scores of older children and adults (Tukey HSD $p = .001, d = 0.49$), with adults identifying more melodies correctly than older children.

Second, identification scores also differed significantly by experimental condition, $F(2, 147) = 117.49, p < .001, \eta^2_p = .62$. Post hoc tests (Tukey HSD) revealed significant differences between all pairs of conditions: intact versus noise-filled gaps ($p < .001, d = 0.58$); intact versus silence-filled gaps ($p < .001, d = 1.94$); noise-filled gaps versus silence-filled gaps ($p < .001, d = 1.38$). Overall, identification in the intact condition ($M = 9.17, SD = 1.50$) was superior to that of the noise-filled gaps condition ($M = 8.04, SD = 1.94$), which in turn had superior identification scores to the silence-filled gaps condition ($M = 5.21, SD = 2.04$).

Third, Age Group interacted significantly with Experimental Condition, $F(4, 147) = 2.96, p = .02, \eta^2_p = .08$. The young children showed an effect of Experimental Condition, $F(2, 63) = 59.37, p < .001, \eta^2_p = .65$. There were significant differences between all pairs of conditions (Tukey HSD: all $ps < .001$). There was also a significant effect of Experimental Condition for both older children and adults, $F(2, 57) = 46.28, p < .001, \eta^2_p = .62$, and $F(2, 27) = 30.73, p < .001, \eta^2_p = .70$, respectively. However, for both the older children and adults, the difference between identification scores in intact and noise-filled gaps conditions was non-significant (Tukey HSD: older children $p = .13$; adults $p = .42$). All age groups demonstrated a noise-filled gaps over silence-filled gaps

advantage in identification (Tukey HSD: young children $p < .001$, $d = 1.87$; older children $p < .001$, $d = 1.85$; adults $p < .001$, $d = 2.56$).

It is also interesting that for both the intact and noise-filled gaps conditions, there were significant differences between all age groups, with adults outperforming the older children, who in turn outperformed the younger children (Tukey HSD: all $ps < .01$). This pattern was not found for the silence-filled gaps condition. Whilst the identification scores of young children were significantly lower than those of the older children (Tukey HSD $p < .001$, $d = 2.08$) and the adults (Tukey HSD $p < .001$, $d = 2.36$), there was no significant difference between the older children and adults in their identification scores (Tukey HSD $p = .72$).

Discussion

The primary aim of the present experiment was to investigate age differences in the perceptual restoration of musical melody. The findings have three key implications for our understanding of perceptual restoration. First, all three age groups showed evidence of perceptual restoration; their identification of the fragmented melodies was better when the missing fragments were replaced by noise, then when replaced by silence. The benefit of noise-filled gaps over silence-filled gaps is similar in young children, older children and adults, supporting the finding of Newman (2004) in the speech domain. However, identification of melodies with noise-filled gaps increased significantly with age, with a considerably larger increase between young children and older children, than between older children and adults. This indicates that the ability to combine previous knowledge with incoming acoustic information develops significantly

between the ages of 4 and 11. Crucially, whilst perceptual restoration does operate in 4- to 6-year-old children, the ability to identify fragmented stimuli where missing sections are masked by noise is still to undergo considerable developmental change.

The second implication relates to the general effect of signal disruptions on perception. Based on the finding of a greater difference between identification of intact sentences and those with noise-filled gaps, Newman (2004) reported that children's ability to accurately repeat the sentences was more greatly disrupted by the presentation of partial input than adults. Here, we show that in the case of musical stimuli, young children also seem to be more greatly affected by signal disruptions than older children and adults. Young children's identification of melodies with noise-filled gaps was significantly inferior to their identification of intact melodies; a difference not evident for the older children and adults. This may indicate that the older children and adults were experiencing the full restoration 'illusion', where intelligibility of stimuli with noise-filled gaps is restored to the extent that it is similar to that of an intact signal. It is therefore possible that whilst noise improved intelligibility of the melodies relative to its absence, the youngest children were not experiencing the full restoration 'illusion'. This suggests that whilst perceptual restoration does operate in the musical domain in young children, their perception is more greatly affected by disruptions to auditory signals than perception in older children and adults. This appears to be a domain-general deficit to auditory perception, rather than specific to speech perception. Investigation of perceptual restoration effects in young children, and finding possible ways to develop them, thus becomes a key concern based on the finding that noisy disruptions can have a detrimental effect on young children's auditory perception.

The third implication of the findings relates to the potential benefit that the conditions for perceptual restoration (i.e. masking noise) provide over interpretation of fragmented signals with no masking noise. Examination of identification of melodies with silence-filled gaps, where young but not older children are significantly inferior to adults, suggests that young children have particular difficulty interpreting fragmented musical signals where missing sections are not occluded by noise. Consequently, perceptual restoration emerges as a critical mechanism for these young children. If identification of disrupted input with silent gaps is particularly difficult, this suggests that young children are unable to make the same inferences that older children and adults can make in the process of perception. Thus, occluding noise plays a key role in allowing young children to make sense of disrupted input. This conclusion is directly in line with recent accounts of the ecological importance of perceptual restoration (e.g. Husain, Lozito, Ulloa & Horwitz, 2005).

The operation of perceptual restoration for all age groups tested indicates that from young childhood to adulthood, music perception displays a preference for global coherence. Whilst stimuli in both the noise-filled gaps and silence-filled gaps conditions contain disruptions at a local level, only by replacing missing sections with occluding noise does the stimulus satisfy the requirement of a perceptually coherent whole. Musical signals are particularly important for children, playing an important role in the development of language (Masataka, 2007), and current educational practice encourages the use of music as a learning device in many areas of the curriculum. Therefore, active music perception in children, where missing input can be reconstructed, means that the

detrimental effects of everyday noisy listening conditions on children's learning and development are minimised.

A key goal for future research is to find out why young children show a domain-general deficit to perception of disrupted sensory input relative to adults, and whether perceptual restoration in children and adults, and in children of different ages, is mediated by the same perceptual processes. It is possible that age effects signify a different trade-off between top-down and bottom-up processes in auditory perception, with adults emerging as less affected by signal disruptions than young children because adults can make better use of top-down contextual cues when interpreting disrupted input. As a result, acoustic disruptions to the signal have a less detrimental effect on their perception. Further research into the course and cause of development of perceptual restoration is currently underway, and may help to reveal the important abilities underlying the operation of a mechanism that represents a crucial adaptation to noisy listening conditions.

There appears to be something fundamental about our ability to fill in gaps in sensory input. There is also emerging evidence that this is not just a fundamental property of visual and auditory perception, but also tactile perception (Kitagawa et al., 2009). A further goal for future research is to investigate the relationship between sensory filling-in processes in children's perception across domains. Here we have presented preliminary evidence suggesting that just as in visual perception where things do not have to be seen to be perceived, neither do sounds have to be heard to be perceived. The presence of these abilities in childhood, and in multiple auditory domains, suggests that they form an important part of the way we experience our sensory world.

Footnotes

¹For all three age groups, there were no significant differences in the mean age of the participants allocated to each experimental condition.

²In order to study perceptual restoration in children white noise was used, as the well-established effects of white noise in experiments on the perceptual restoration of piano melodies which clearly demonstrated the effect provide benchmark data (e.g. Kaminska & Mayer, 1993; Sasaki, 1980). In future studies the effect of the acoustic overlap between signal and noise can be evaluated.

³Nursery rhymes and play songs are seen as universally familiar regardless of age and as such are appropriate for use with adult participants. They are often used in tests of adult music perception, including the musical perceptual restoration experiments reported by DeWitt and Samuel (1990).

⁴The song familiarity questionnaire was completed by the schools on behalf of the child participants, to confirm that the songs were taught and sung on a regular basis in the early years of the school.

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Appendix: The name, duration, time signature and key signature of the 15 stimuli presented

<i>Nursery rhyme</i>	<i>Excerpt duration (s)</i>	<i>Time signature</i>	<i>Key signature</i>
Baa Baa Black Sheep	5.90	4/4	C major
The Grand Old Duke of York	5.25	4/4	C major
Twinkle Twinkle Little Star	5.75	4/4	C major
Happy Birthday to You	4.75	3/4	C major
The Wheels on the Bus	5.32	4/4	C major
The Hokey Cokey	6.50	2/4	C major
Row, Row, Row Your Boat	4.25	4/4	C major
Old Macdonald had a Farm	4.50	4/4	C major
London Bridge	4.50	4/4	C major
Jack and Jill	4.39	2/4	C major
Incy Wincy Spider	5.00	4/4	C major
Humpty Dumpty	8.00	2/4	C major
Hickory Dickory Dock	5.50	4/4	C major
If You're Happy and You Know it Clap Your Hands	6.75	4/4	C major
Heads, Shoulders, Knees and Toes	3.25	4/4	G major/ C major

Figure 1

Figure 2

Figure Captions

Figure 1. Score of the first phrase of ‘Twinkle Twinkle Little Star’ and sound profiles of the intact, noise-filled gaps and silence-filled gaps versions of the stimulus.

Figure 2. Mean number of melodies identified correctly ($\pm$ SE) by young children, older children, and adults, in each of the three experimental conditions (intact, noise-filled gaps, silence-filled gaps).