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Understanding the Benefits of Ultra-Fast Processing on a Molecular Level

Presenter: Francis Kuk, PhD

- Welcome to today's course, "Understanding the Benefits of Ultra-Fast Processing on a Molecular Level," presented by Dr. Francis Kuk from Widex. This month on Audiology Online, we're celebrating innovation in the hearing industry with our fourth industry innovation summit. Thank you for joining today and we hope to see you in other summit courses throughout the site in the year. We'd like to thank our title sponsor CareCredit and all of the companies who are participating in this year's events. And now it is my great pleasure to turn the microphone over to Dr. Kuk.

- Good afternoon and thank you Melissa for the kind invitation for us to speak on this particular topic on the understanding the benefits of ultra-fast processing on a molecular level. To begin with, what I like to share is, let me advance the slide. I am an employee of WS Audiology. I work in the capacity of Clinical Research for Widex and there's no non-financial relationships. Hopefully, by the end of this hour you will be able to understand and articulate what is the mechanism behind ultra-fast or ZeroDelay technology in terms of how they preserve the naturalness of sound and some of the neurological perceptual evidence that support the benefits of this particular feature. I will break the agenda into kind of like four or five parts.

We'll first talk about the background for ZeroDelay technology and start with the inspiring survey data that we have collected on how effective it is leading us to examine the benefit on the more molecular level from the acoustic measurements, the neuro representations, and the perceptual impact of that. Hopefully, giving us some implications as to what to do with this particular technology. So let's begin from where it should all start. And that is why is there processing delay? What happened? And if you still remember this very schematic diagram of a digital hearing aid, we know all digital hearing aid has these components. You know, there's the microphone that picks up sound and that this gets processed, converted into digital form and the digital signal processor manipulates the signal and then it goes out of the receiver.

So this process, I think everyone is very familiar with and when we talk about processing delay, we are talking about the time between the sound getting into the microphone of the hearing aid to the time that it gets out of the receiver of the hearing aid. Meaning, the process and delay because there is digital signal processing because the hearing aid, digital hearing aid, needs to do work, converting the sound, manipulating the sound, using say for instance, different frequency domain processing or time domain processing, or things such as noise reduction, or feedback management. All those processing takes time and that's why there is the processing delay. Now, if it is a very sophisticated chip, then the processing delay might be very small and if it is very complex type of processing, then the delay may be longer, okay?

So the processing delay is a combination of how good the chip is and how sophisticated the processing is and is a necessary part in all digital signal processing. Unless you go back to analog hearing aid, then you might not have such a big issue. So the processing delay in a digital hearing aid is with this red-framed region. And because it's a necessary evil I guess, of digital signal processing, engineers have to figure out well, so we know that it is gonna cause some kind of delay, so how do we make sure that this delay does not affect what I want to do? So back 10, 15 years ago when we introduced the digital, the wireless hearing aid, the clear hearing aid, we did a survey looking at the report on how delayed affects perception, you know?

And what we know is if the delayed is 150 milliseconds, that long there is going to be a visual and auditory dyssynchrony. Meaning, what I hear is much later than what I see. And of course, that's not good. And for those of you who are my age, then you remember back when first TVs were digital TVs, some TV actually have this synchronous, it doesn't match so to speak. But of course, that's much more improved and because we know what the effects are on the delay and back in those days Bluetooth about 70, 80 milliseconds, but when the delayed is much shorter like to 30

milliseconds, you still can perceive some kind of an echo effect, this hollow effect. And when it is shorter than that 10, 30 milliseconds, there is this metallic sound.

You know, the quality of sound is not acceptable, okay? But what people found back then is well, but if we drop the delay, if we can make the delay, streamline everything we do, make the delay less than 10 millisecond, then it seems to be okay, it's quite acceptable, you know, in the sense that we don't hear easily those echo and we don't seem to have have some effect in terms of speech understanding and so forth. So it is accepted at that time. 10 millisecond delay is a good working target for most people. And indeed, if you look at that, the processing delay among most major manufacturer is under 10 millisecond. You can see someone with eight millisecond, you know, this other one is about six, seven millisecond, someone else is five millisecond.

But even at that time, back 28 years ago, when we first introduced digital hearing aid, because of the time domain processing, we were able to keep the delay of the hearing aid to as little as two milliseconds in the high frequencies and to perhaps about 5 dB of five milliseconds in the very low frequency. So we are way better above this being acceptable criteria that we have all set up, okay? But then, so it's all good that you say, well, everyone is within the framework of what is acceptable, but then the question that we ask ourselves is, well, is acceptable good enough? Is something being acceptable good enough? And let me show an analogy here. So let's take a look at this picture.

So here's a picture, let's assume that this picture was taken 50 years ago. You know, the coloring is poor, with the resolution of cameras are are not very good. But when I show you this picture, given the time aspect of when this picture was taken and shown, I ask you, is this acceptable? Then you have no choice but to say, yeah, this is acceptable. At least I can make out a face. It looks like a good looking boy, he's wearing glasses and all that kind of thing. So that's acceptable if we were 50 years ago, because of the limitations with the technology. But if on the other hand, I show

you this picture today and ask you, is it acceptable, you'll probably not say this is acceptable because you have seen picture on my right hand side.

Nowadays, pictures are like this to be acceptable. You know, where you can see the finer details in the child's face, you can even see the reflection on the glasses of this child, of the sunglass. You can see three men are probably fighting each other and all that kind of thing. So what is acceptable years ago may not be acceptable today because the standard that we judge acceptability also needs to change with time, also needs to change with technology, okay? And acceptable is something is acceptable if it provides all the details that we are known to depend on. And that particular word details is very, very important when it comes to speech understanding. Now here is a model that we adapted from Ronnberg on the ease of language understanding model.

And what this model tells us is, well how do people actually understand speech? So it started with phonological information. So information that comes from all modalities, visual, auditory, tactile and whatnot, and it actually goes through the brain, goes through the long-term memory part of the brain and it does a very simple quick match procedure. And if what we got from our sensory system matches with what we remember in the long-term memory, then there is recognition, okay? Then we know what it is, then we see what it is, we understand what it's, we remember what it's and all that kind of thing. And this is an automatic process. It really doesn't need you to work at all, okay?

And that's what we call implicit processing. If on the other hand, what we got from the input from the brown box here is incomplete, okay? It doesn't have all the necessary details, then you can imagine, then when we come to the blue box where the brain has to do a matching with the long-term memory would not be complete because it doesn't have all the information that we need to have, right? So in that case, it goes through what we call an explicit processing where the brain would now need to pull

information from everywhere within the brain to try to understand what is going on. There is going to be the filling in, there's going to be the guessing part.

And if you have the brain power, if you have the working memory to sustain it, then you are okay, then you can still understand what is going on. But if on the other hand, for those with a poor working memory or whatever solution issues, then getting into this explicit move would increase the demand, makes it more effortful for the listener and make it more difficult to get optimal performance. And that's why details is so important. And what is important in this model, which is supplemented in a few years later, is that the goodness of this phonological information is also very much dependent on this stage called the auditory scene analysis. So this is the part where the brain breaks down the sounds into different categories and then we group them so that all these details can be supplied to the brain for understanding.

And this part, this scene analysis has several factors that relate how good this process is. And these are what we call input related demands. And one of the very important aspect of the input related demands is the transmission channel is how the sound goes through a device such as a hearing aid, how would the hearing aid alters the sound so that you get a different set of information that comes out. So that is why a hearing aid that can keep all the natural sound would facilitate this understanding process. And that's why it is important. And that is why if we can keep all the natural cues, the more likely this process from blue to green would take place.

And that's why it is important. And to a certain extent, we can also liken this naturalness from the hearing aid processing to organic food. You know, we talk about organic food and we like organic food because it's more natural, because it keeps all the nutrients, all the minerals, all the fibers versus junk food does not have a lot of those things in there. And that's why we like it because it's good for us and it's kind of like hearing, If we can keep all the features within the sound that would be a better

thing for the hearing impaired person. You know, just a couple days ago when I was finalizing on these slides here, I saw this one of these chicken soup KOL was putting out, you know, what are the things that you can do to give you energy to make you more positive and the things that takes energy away from you to make you more negative?

And if you look at this here, eating whole food is one of the top things that would actually give you more energy and it kind of makes sense, right? I mean, it gives you all the fibers, all the vitamins and you absorb it is easier on your stomach digestive system and that gives you the energy. Whereas, if you eat junk food, it does not have a lot of the naturalness of sounds, it makes it more taking away more of the energy from you. And to a certain extent you can kind of imagine this, you know, a hearing aid that keeps all the details, if it can make listening effort better. If it doesn't require as much listening effort because of what it does, then it could give you more energy.

You might feel less tired at the end of the day, which we all know hearing impaired people have because of the effort that to they need to show while they are in a listening situation. So I thought that is a very interesting thing, okay? And it's precisely because of that reason that we should keep the naturalness of sounds that we develop this ZeroDelay technology. You know, even though back 28 years ago when we introduced the sensor digital hearing aid, we get an average delay of about 2.5 millisecond, which is already the best. We still think, well, we need to do better because we know that there's still additional details that we can keep if we make the delay to a 0.

5 millisecond delay, which is essentially what we did with a ZeroDelay technology. So back a couple years ago, we had this survey where we introduced the product and we asked people how they like the hearing aid, how they like the ZeroDelay or the ultra-fast processing, comparing that to their own hearing aid. So we have people, first of all, rate the hearing aid and then they wear the MOMENT PureSound program for

three weeks and then they rate the hearing aid, the PureSound again, then we switch back to their old hearing aid, have them rate their old hearing aid, and then we switch back to the MOMENT hearing aid and have them rate the MOMENT hearing aid, the PureSound program at the end of the 7-week survey period.

So at the end, here's what we found, okay? So on the survey we asked them in terms of how natural the sound is, you know, the sound being natural, the sound being clear, my own voice is natural, the impression of sounds being what they expect. With their own hearing aid, which is the lighter color bar, you see that they do pretty well, okay? Most of the ratings were on the agreed or somewhat agreed, but with the MOMENT PureSound program, we see the darker bars being a lot more they agree and lots more on the strongly agree as you can see in all four categories of the natural perception here. When we ask them in terms of how satisfied they are with the hearing aided noise, we saw very similar things.

Their own hearing aids, they were satisfied and somewhat satisfied and somewhat dissatisfied. But with the MOMENT PureSound, most of them were satisfied or very satisfied also with the noise. And on the sound quality, they also rated being very satisfied as well as satisfied. So this is all very good and most people would say, well, I can just stop at that because you show me the evidence that it is working and people like it and after all, it's people liking it that that is important. Yeah, that is true, okay? But the fact that you are listening to this seminar here, the fact that you are listening that you give the attention to know more about it tells me you have this inquiry line.

And we always ask, you know, people will inquire and might would say, well, don't just give me all this service type research data. I like to know why, I like to know how it is giving us this kind of data, okay? Why does it that people think this is more natural? What is it about this low processing that gives you this low delay processing that gives you disadvantage? This kind of asking why and getting to the bottom of the evidence

chain. You know, why does it is what I call the molecular approach. You know, this is deep diving into, well, what is the evidence at the different, more basic level that perhaps help to give us this information about people being more happy with the device.

So the molecular approach that I used in the title is basically trying to understand how and why it happens. So if you look at this figure over here, so we start now with the answer as to why this thing happened. When we are wearing the hearing aid, we know they have a processing delay. And what the processing delay simply means that the sound is gonna be arriving in the air canal later than what this being at the microphone. Now, of course, we all know if someone is wearing a hearing aid like a RIC type hearing aid with a vent in the hearing aid, there is some direct sounds that leaks through the vent that goes into the ear canal, okay?

So now when you have two sound sources, one directly from the hearing aid and one through the vents from the environment going into the ear canal, there is going to be a mixing of sound, okay? And the mixing of sound is what you can see over here that I'm circling. And this mixing of sound, this is the frequency spectrum. And you can see there is a lot of combs there, like teeth of a comb and that's why engineers called it the "comb filtering effect," meaning a mixing of sound so that the resulting spectrum looks like a comb. And indeed, if the traditional, if the majority of hearing aids that we have been today instant fit RIC type hearing aids, where it's inevitable that you will have some degree of leakage, comb-filtering is a real danger, it's a real defect than many of your hearing impaired patients would encounter.

And this comb-filtering effect can be seen in two dimensions, you know? So back in the days when we first have this, we say, well, let's measure it and see how well they changed the spectrum. So what I'm sharing here with you is the output on KEMAR's ear when we swift through a different frequency through the ear canal with an open ear

tip, okay? So there is no blockage of the air canal and you can see this is the natural sound that goes into the ear and at the eardrum. And the blue line here is the ones are the output from the MOMENT hearing aid with the PureSound connected to an open ear mode and with two other manufacturer, you know, with different delays on the hearing aid and also using the same open ear tip.

And what you can see here is when you compare the MOMENT hearing aid, especially the region around 2 to 3,000 hertz with the unaided, they look very similar. You know, you see the peaks, and you see a little bit more because of the amplification and whatnot, but in general, it is very smooth. Whereas, if you look at manufacturer one and manufacture two, then you see more of the peaks and the values, you know, peaks, of course, are what we call the resonance. This is when two sounds are added together and the diffs are the cancellation of sounds. So some sounds are actually added to the original sound that goes into the microphone and some sounds are actually taken out from that, resulting in what we call a spectral distortion from that perspective.

And you can also see this distortion occurring in the temporal domain where you have the sound coding, where we have a broadband noise going into the hearing aid. And so we have the broadband noise there and then we have a gap that we introduced at about 100 millisecond and then we have a gap of different size and then we continue with the noise. So if you take a look over here, then with the unaided, here's the gap and with the PureSound, now the gap is still about at the same place occurring like the unaided situation. This is now at the air canal of KEMAR. Whereas, if you look at manufacturer one and manufacturer two, the gap is now displaced to about 110 milliseconds.

You don't see the gap here anymore, okay? It's different. And if you look at longer delay, it is also quite different from what we see in the original unaided condition. Meaning, this delay from the hearing aid actually changed the waveform of the sound

that goes into your brain. So the first tool, the first evidence that we have is really what we call the basic acoustic measurement. And of course, you are not gonna be happy with that because acoustic measurement does show a difference, that that difference make a difference from the neurological aspect or at a higher perceptual aspect. So we say, well, let's answer the question. So let's see if we can measure some electrophysiological responses to show that this delayed difference does make a difference.

And the tool that we use was called the frequency following response, or some people call it speech ABR back in the days. And the reason why they is called a frequency following response is that the stimulus that we use in this particular measurement is a speech, okay? Is a disyllable that goes into the ear that gets processed in different stages, it goes and mixes in the inferior colliculus and then it goes up to the brain and so forth. And of course, we also know that this pathway here has an inferior pathway, meaning whatever is happening in the brain can add to shape the goodness of this sound that we've measure on top of the patient's scalp.

So you put the electro stereo, you present the /d/ or the /b/ sound, you measure what is coming out and what you measure coming out looks like what you put in. That's why we called it the frequency following response. And what you put in here, I mean, this recorded response here can actually be divided into two parts that shows you what is the temporal envelope, you know, the up and down part of the sound as well as the temporal fine structure. You know, what frequencies actually get processed by the brain that goes up to the higher cortical center. And it's the temporal envelope that we are looking at in this particular study because this is the part that reflects how well the brain phase lock to the stimulus.

By that I mean, how well the brain pins on how well the brain latches on, on the peaks of the sand so that that envelope information is conveyed to the brain. And

phase-locking is important because the phase-locking ability, you know, the phase-locking ability that we measure through the EFR gives us some information about the goodness of the neural inputs to the brain after it has been modified by whatever inferior input from the brain. And many of the research study, especially from Dr. Linda Krause's office research lab shows that the better speech noise ability you have, the better phase-locking ability you have. And she have also demonstrated that musicians in general, have better phase-locking and to train people on something, they also get a better phase-locking, I.

e. the temporal envelope would be good. And when you are getting older, when you have a hearing loss, all of those things would decrease, okay? So looking at that gives us very good insight in terms of how well the brain captures and retains that information. So we did it with a /da/ stimulus. So we presented the /da/ sound and this is the envelope of the /da/ stimulus. And you can see, of course, this is the vowel part, the /a/, within the /da/, and you can see some of the peaks occurring in the signal at about 10 milliseconds, right? Suggesting this is a sound with a fundamental frequency of about 100 hertz. So this is what the stimulus looks like and what I'm sharing with you now is what the EEG, what the envelope following response looks like.

Okay, this is manufacturer one in which you can see that the first peak and maybe the second peak actually follows the stimulus quite well, but not so much with a third and fourth peak. You don't really see that strong peak there at all. And if you look at manufacturer two, it's a little bit better, with the purple graph here. The first and second, you do see the third and fourth, not as strong, but it is there. Now, here is what we have with the MOMENT PureSound in blue. Now you can see that difference, the peaks are very well-defined. The peaks actually synchronizes with the input sound that we were showing you. And that, of course, is very impressive, okay?

Now this is the study that we have done, we have completed at our lab maybe two years ago, two and a half years ago. So since that time, we have actually asked Dr. Anderson, Samira Anderson at the University of Maryland to essentially duplicate the study. And she found exactly the same thing, but her data are presented in a different way. So what she is showing us here is the synchrony, you know, meaning how well the peaks lined up with the original signal. And if you have a good synchrony, you will see a lot of yellow thing there. And if you have good, no good synchrony, poor synchrony, basically everything will be blue. So the top one here is the 0.

5 millisecond and you can see a lot of very good synchrony within the auditory system with the signal, whereas you don't see that at all with the five millisecond and you see a much weaker synchrony with the seven or eight millisecond signal, okay? Essentially duplicating, replicating what we were able to show our people and these results are published in the last month's issue of the EAR and HEARING. And I would strongly urge that you take a look at that. So from the electrophysiological aspect, we see that difference. So what about from the next higher level? You know, after all, these sounds, we see the acoustic difference, we can measure that electrophysiologically, it's going into the brain in a different way.

What about perceptually? Does it have any impact on safe speech understanding or some other aspect of processing? So if you remember what I showed you earlier, it does cause the spectral distortion, right? I mean, with the low delay, with the longer delay we can see that. Now, one of the things that we know is that vowel sounds, they carry different spectrums and different vowel have different spectrums. And if the vowel doesn't sound the same, if the vowel is distorted, it's alter in some way, it doesn't sound the same. And people call that difference the coloration, you know, the coloring of this vowel is different, it has a different color so to speak. And it's simply the difference between what you put into the hearing aid and what gets out of the ear canal, which is the mixed spectrum.

So there is the coloration aspect that created, that gives you the subjective difference and it could potentially affect vowel recognition or vowel identification. So we did a study then with that in mind they say, well, okay, so let's now ask people to discriminate different vowels, so the a-e-i-o-u or you know, and so forth. So there are five different vowels and each one of those vowels are processed with the three different delays, the 0.5 milliseconds, the five milliseconds, and the eight milliseconds. And what we did is we have this discrimination task so that people hear three sounds, a-a-a, kind of like that, okay? And the middle sound that you have heard is very different.

I hope you have heard that. So the patient's task is to recognize which one is different. So it's a three alternative fourth choice task. If there's physically absolutely no difference among the three and the patient, just guess what it is, then that would have the correct rate of about 33%, okay? But if the three sounds are very different, if the sound was a longer delay, really sounds very different from the no delay, then the correct identification would be very high. You would see more than a 33% difference. And indeed that's kind of what we found. So what we can see here, so the y-axis is the performance, 33% being adjacent, and we can see with the 0.5 millisecond, the low delay technology, we get a percentage of about 42%.

Yeah, people can still get some clue that it is not exactly the same, but it's very small. Whereas if you look at the five and eight millisecond delay, the difference is much higher, about 55% on average difference, okay? So coloration, this does make the sound, especially the vowel sound, very, very different to the point that people can perceive it and perhaps some identify that. So that's one aspect starting from the spectral domain. Now, if we also remember that it changes the envelope, it changes the shape of the sound that goes into the brain as you can remember from here. So

now if we also recognize, if we also remember speech is actually a sequence of time ordered events, okay?

You hear one word from me, you hear a second word from me, the third word from me, if you break it down into more of the phonemic level, you'll hear one syllable after another syllable. There is a timing pattern to what I just say because it is the time aspect that the brain process. So if the delay actually makes this gap looks very different, how would that affect speech, especially speech that is dependent on the timing aspect. So we have now then taken a look at it and see, well, does it make a difference? So what I have here is a stop consonant syllable, the /d/ syllable. So there is the noise first at the beginning, so this is the original sound, the /da/, and this is the onset of the vowel sound, so the voice onset time here.

So from the beginning we start opening, closing the lip to the opening, this noise burst here is what we call the voice onset time. And it takes about this much time before it goes into the voicing. Now, if we have this sound and delay this sound by particular time, so everything is essentially delayed by this much. So whatever is before here at this point, now comes to this point, whatever is here at this is shifted into this part over here. So this is just the delay sound. Now, if we add the original sound in the delay sound, meaning the comb filter type sound, we actually see something that looks like the third panel here, in the sense there is the initial sound, which is not audible and there is this delayed sound plus the original sound in the middle, which is the red one.

And this delayed sound, which was part of the original and delayed sound except now, this is mixed with the voice sound. So it actually does sound like voicing. Voicing would've started at this point and it'll continue within this. So in essence, you can see that if you look at a mixed spectrum, the comb filter spectrum, the voice onset time, the noise burst is actually shorter, you know, than if you did not have this delay. And indeed what I was alluding to is the phenomenon of the voice onset time. We know for

like the stop voice consonants, like the /d/ or die, the /d/ here has a much shorter voice onset time. It takes about 30 seconds when you do /da/, and then for you to jump to the /e/ or the /i/ part.

Whereas, with the unvoiced stop consonant /t/ or tie here, this duration here, this noise burst is actually much longer. So we know that /d/ and /t/ are different, primarily based on this voice onset time. So the question that we have is, if that is true, could it affect the voice onset time if we have different delays on the hearing aid? And before we did the study, we actually measured the spectrogram with the zero millisecond delay, with the 0.5 millisecond delay. This part here that I'm moving around my cursor, this is the noise burst, okay? So this is the start of the aspiration. This is the voice onset type here. And if you look at the 0.5 millisecond delay is pretty much aligned with the direct sound, but if you look at the five millisecond delay or the eight millisecond delay, you see the shift, okay?

Effectively making this noise burst in the longer delay situation much shorter than what it was in the 0.5 millisecond or the zero millisecond delay. In essence, if we think about it, if we remember the definition of a voice stop consonant versus an unvoiced stop consonant, if in the process of the delay, we have effectively shortened the noise burst, okay? So from whatever millisecond shortened it to this amount here, we are making a voiceless sound like the /t/ sound sound more like a voiced sound like a /d/ sound, okay? So this is what we expect that would happen, but this is what we hypothesize that would happen. So we did a study and, of course, many of you who had the speech science class before or hearing science class before you remember the term categorical perception as a way to study how well the brain organizes, you know, the identification of different sounds and so forth.

So we did a categorical perception task where we have the /d/ and the /t/ sound, you know? Because they're different by the voice onset time, we divide that difference into

13 equal intervals and we presented those sounds within each one of those intervals and have the subject identify what it's, whether it's a /d/ or whether that's a /t/. And we plot the graph that shows us what is the percentage, what is the proportion of time that the subject would identify it as the voice list or the /t/ sound over here, okay? So you can see that if it is over here, that means the sound is primarily identified as a /d/ sound. If the sound is over here, it is primarily identified as the /t/ sound or the voiceless sound.

So this is the result of the different delays, the zero millisecond in black, and the 0.5 millisecond in blue, five millisecond and eight millisecond, and so forth. So first thing you can see is that there is a shift, you know, delay on the hearing aid actually does shift the category boundary, making it more towards one side than the other is actually pushing it seems like to the right side board. So if we take a look over here and now, make do some number kind of interpretation. If we have a sound that has a voice onset time, let's say of seven interval, which is like half a 15 millisecond, most of the time, 70% of the time the patient will say, if this is a no delay sound, 70% of the time the patient will say this is a /t/ or a voiceless sound.

If on the other hand, this same sound is now processed by the eight millisecond delay sound, this same sound would only have a 20 or only have a 30% chance that the person is gonna recognize it as a /t/ sound. Meaning when you have the longer delay, you make a /d/ sound like, or you make a /t/ in voiceless sound more like a voice sound. It does make a difference, it makes a confusion on the patient listening to these sounds. And indeed it is significant that even the 0.5 millisecond delay is different from the no delay, but it is dramatically different from the eight or five millisecond delay. And that I think is an important thing. So it does make a difference.

And, of course, we want to know what is the realistic impact of this, you know, I mean, people are telling us it sounded good with a very small delay, but what effect does it

have realistically on speech? So the studies that we did on the speech perception aspect shows that it does, the delay does distort the molecular base of speech sound, changes the voice onset time, changes the coloring of different form of distributions and all that kind of thing. And it's noticeable. People can tell that difference. Now, not everyone would make an identification difference, meaning that people are probably not gonna say that the /e/ now sounds like a /b/ or /a/ type sound, because that requires a much larger difference.

But in situations, where the identification may not be optimal, maybe when you have a non-native speaker who is already speaking with a different vocal format or a different voice onset time when someone is speaking at a much faster rate, okay? Or when someone is a foreign listener listening to your speech, and then you already have like a quote-unquote, a "different" type voice onset time characteristics or the level difference, or when there is a lot of noise in the environment or when their person already have poor recognition, or poor frequency resolution and so forth. Those are the situation that makes it more difficult, okay? People can recognize the difference. They may not identify it incorrectly, but they are spending more effort in their recognition and identification, okay?

So it will still be very important, okay? Because of the additional energy that people have to put in to understand what is going on. So realistically, it does have that potential impact on speech understanding. So we are done with the acoustic basis, we are done with the neurological basis. We also have some perceptual evidence to support why it could affect speech understanding. So here's another study that we look at the perceptual aspect, primarily because we don't understand, okay? So when we first introduce the PureSound or the low-delay program a couple years ago, people were raving about it, but the things they say did not make any sense to us. They say, well, now for the first time I can localize sound.

I know where sound come from and when I'm wearing this, it's almost like virtual reality. I get this 3D perception, you know, it feels like the space is more open to us. And then, you know, and they use terms like localization, which to me is the ability for you to say this is 30 degrees, this is 40 degrees and whatnot. So we don't understand this because we didn't expect this would change that kind of perception. So we try to understand and we looked at different literature and see if there was any cues for us to kind of understand this. And lo and behold, we came across literature in the architectural acoustics, okay? And there's a whole big discussion on the psychology, you know, on the perception different acoustic parameters, different structural parameters could affect the acoustics and how that could affect the individual's perception.

And as it turns out, that may be the reason why people perceive more of this spatial awareness. So as it turns out, the reflection pattern of any room, of any enclosure is very important because it tells you something about that environment. So, and we all are familiar with that inside a room, if there's someone speaking, we hear the direct sound, you know, this is, of course, the most direct sound, but it's also the sound that reaches our ear in the shortest amount of time. But of course, my voice also get radiated within the room, hits the wall and it comes back to me or comes back to the listener as reflected sounds, okay? And if you plot the magnitude of these reflector sounds over time, you can see there's the first reflection and there are many other reflections over time, and this gets smaller and smaller in amplitude.

And of course, we all have learned from school that reflection is not good. More specifically, we heard that reflection, especially the late reflection, which we call reverberation, is not good because it destroys the signal to noise ratio. But the earlier reflections on the other hand, are not. The earlier reflection actually tells you something about that particular environment. Whereas the later reflection, the reverberation destroys that perception even more. It doesn't help, it actually makes it worse, but the

earlier ones is not. This initial reflection, the time that it takes for the sound to reflect back to the listener is what we call initial time delay gap or the ITDG and, of course, the ITDG is the loudest compared to all other reflections.

And this initial reflection is changes, you know, with the size of the room, a smaller room there is a shorter or time delay, whereas with a larger room, there is gonna be a longer time delay or when the listener is closer to the wall versus the listener is farther away from the wall, that also gives you a different reflection pattern. And as it turns out, this reflection pattern tells us a lot about our environment, okay? A lot of times, you know, for many of us, we see well, we hear well and even though we, whatever comes into our ear doesn't register, but we can actually reconcile that with what we see. So there is a visual and audio coordination so that we think we see what we think we are seeing, okay?

So is this reflection pattern that allows us to say, to ask the question, do I hear what I'm seeing? You know, is it really true that John is talking in front of me here? Is it really true that I'm hearing Francis from this loud speaker? So we affirm this. Do I hear what, what I hear sound real, okay? So you should be hearing me like I am here speaking in a classroom because of the mic, it's less reverberate. But if you are seeing me and the picture of where I am is not, okay? It is more like a disco, then you will say, well, what I'm hearing doesn't sound real because it doesn't jive with what I'm seeing.

And from this initial reflection, we also know the sign, shape and materials of the room, where I'm in the room, how far is the speaker from me? And in some situations, it makes us to adjust our behavior, you know? So it's kind of like when you talk in the church, okay? That huge echo gives you this solemnness, type thing, okay? This impression. And that's really why you tend to speak slower, you tend to speak softer, because you feel that this is a solemn place. You change your behavior to reflect that. All those have to do with the visual and the spatial type information that we get from

the reflection pattern. So we ask ourselves, so if that is the case, and we also know hearing a delay processing, changes something.

So now we actually hearing two sounds and it's are mixing the two sounds, but it interfere with the reflection pattern that is originally dome, you know with the hearing aid processing they interface with that and with that affect the way I perceive things in the spatial domain, and this is, of course, our speculation. And the top graph here shows a room without any delay other than no delay either room or no delay hearing aid. And if we see now the middle figure here, a hearing aid was delayed, then you can see the difference between the red and blue line here. And if we add the two together, we are wearing a hearing aid with a long delay and this person is inside the room here, now we can see that the reflection pattern does not look like what it was before, okay?

So can people tell the difference? And would that difference make a difference in the perception of the individual. So we conducted a study and this kind of study, it's very difficult to actually use real people to do because then you have to keep changing the hearing aid with different delays. So we use our friend, KEMAR and we put KEMAR in the room, in our classroom, in different positions. So we put them in the middle of the room, near the wall, at the corner of the room, we then present the word batch to KEMAR in the right ear, and we put hearing aid on KEMAR with different delays, okay? And we record the sound from KEMAR, so the hearing aid one may be no delay, it's just a natural sound, but raised to a level that is the same as all the other situations.

And then we have the hearing aids say with a 0.5 millisecond, eight millisecond as hearing aid three or five millisecond with hearing aid four and so forth. So we record them and then what we did is we present those, record the sound in the classroom through insert earphones, you know, which does not allow for any leakage and it's a very accurate representation of what KEMAR hears in that particular room. And we, of course, make the assumption that what KEMAR hears is what the individual hear, at

least from the acoustic side, you know, of course, the ear can now be modified, but it will modify all the different hearing aids by the same extent. So we recorded these sounds, we presented these sounds to the subject.

And in each hearing aid condition, we presented again in the three alternative force choice. So we presented two sounds that are the same, like for instance, in the center of the room and one sound that is different in the back of the room. And we basically ask the subject, which sound do you hear is different and they have to pick, so makes it easy for them. And when we are done with one hearing aid, we do with the other hearing aid, the third and the fourth hearing aid. When all four hearing aids were tested, we go into another randomization of the hearing aid condition. So we did it 10 times, so that we can get a good average number.

So here's the result, comparing and showing the performance of each subject. Again, this is the three alternative four choice. So chance performance is around 33%. So if someone is below 40%, you know that they don't hear any difference, okay? So we have the four hearing aids, one, two, PureSound and they are native. Each color line is a particular subject. And this is my engineer staff made this, this is called a violin plot. So when there are more subject is giving you a particular response, then you see a fatter figure, you know? So you can see with the native condition, when we are comparing the center versus the corner, most people get a pretty good identification of it. You know, 70 to a higher percentage.

The response is less, is still quite good, you know? With the PureSound program, with the 0.5 millisecond delay, but there are still some people who actually still could not do it like at 40%. But, of course, the situation is worse with the two other competitors when you can see a much wider spread and more data points below the 50, 60% point, okay? So there is some advantage, maybe not that strong advantage than this PureSound is making a very, very dramatic difference. But if you compare this now

comparing the center versus the back of the room, now you can see the PureSound in blue have most of the subject identifying above a 70% level, okay? You can see that this fat portion here represent a lot of the subject is actually getting that to the point that obviously is much better than manufacturer two or manufacturer one, where they do not have that many people who get that recognition and is also better than the unaided condition where you see a spread of performance.

And like this, you get the identical, the precise performance of very close to the 80-90%. Okay, so in essence, what we have shown here, what we're able to see is that delay does make a difference. Delay does make a difference in terms of the spatial awareness that we have about ourself as to where we are in the room, as well as different objects in the room and so forth. And maybe that is the reason why, you know, people wearing the low delay hearing aid for the first time they say, "Wow! It is different" because the cues that I'm getting now, the spatial cues that I'm getting now is very different than what I have before. And the spatial cues that I have is more closer, is much closer to the natural cues than you and I perceived.

And with a long delay, it simply messes up that even though on a very gross level, you still can tell someone is speaking from a 30 degrees, 40 degrees and whatnot. Even with longer delay you can do that, but on a longer delay, this subtle spatial cue seems like it's minimized, it is destroyed. And that's why it's important to keep that especially, you know, for people who are dependent on the auditory cues because they don't have the visual acuity to match what they see with what they hear. And I think that's the implication of this. So to wrap this up, I have shown you kind of like the food analogy that I use, that when you have a hearing aid, when you compare a hearing aid with whole food, ZeroDelay technology or ultra-fast processing is kinda like fresh food versus processed food in hearing aid processing, you know?

In the sense that we know fresh food would retain all the minerals, retain all the fibers and the vitamins, and whatnot. And all that is better for you so that your digestive system, your nervous system, all that has the thing, you know, to supplement it so that it is healthier for you, it's better for your health. Whereas, with processed food, you lose a lot of this, you lose a lot of the important cues, the minor details. You know, food is no longer things for you to sustain life, it's also here to give you a better quality of life. That's why people are talking about whole food, how it's important because with the processed food, this artificial ingredient may not be as good for your health.

And by the same token, you know, we can look at ZeroDelay and longer delay in the same way. You know, when you have the ZeroDelay, it tries to keep the naturalness of the sound, i.e. it tries to keep whatever is in the signal and give it to the patient, you know, so that we do not have to do as much of the implicit processing, guessing, filling in what is going on. It makes it less effortful for the patient to hear the sound because it doesn't introduce the artifact. Whereas with the longer delay, with smear, the finer tempo or spectral cues, it's simply makes it more difficult. You just simply, even though you may identify the words correctly, you still have to fill in.

It makes your listening effort difficult for you. So that's an important point. So the final point I like to make is really what is the implication of this? You know, so how is this gonna help my patients? So if you look at this here, the low delay, if it is the current status of delay hearing aid of less than 10 millisecond, on the surface, it's really not a problem, okay? For people who have a moderate degree of hearing loss or even more hearing loss because these people do not wear any open ear tips, okay? They do not have an open mold because these people require the gain, you need to give them the gain that's why you include the hearing aid and all that kind of thing.

And the low delay has the impact only when there is a mixing of the direct sound and the process sound. Meaning, when there is a vent in the hearing aid coupling system,

I.e. the ear insert. So if you think about this, this restrict to this group of individual, people with mild to hearing loss and then you say, well, mild to moderate hearing loss, that's too bad because you know, most people that I fit, they are wearing, they have more hearing loss, they have a moderate degree of hearing loss or more degree of hearing loss, so this feature doesn't help. That's correct, this feature doesn't help, but remember one thing. If we look at this chart, which I have seen for the last 15, 20 years, okay?

The majority of hearing awareness are people with a moderate to severe degree of hearing loss. A lot of hearing impaired people with a mild to moderate degree of hearing loss, actually about 75% of these individuals do not wear hearing aids. Meaning, even though mild to moderate hearing loss is... No, the people with a mild to moderate hearing loss, there are 75% of the whole hearing loss population. Of this 75% of people, only 10% of these individuals are actually wearing hearing aids. And the number one reason, other than cost, the number one reason why these people do not wear hearing aids is because they say it sounded like a hearing aid, okay? Because of the echo with own voice, because of the echo with the process sound, making the voice onset time different, making the spatial sound different.

That's why people say it sounded like hearing aid speech. So the beauty, the benefit of ZeroDelay technology in our understanding, in our speculation is that ZeroDelay technology, actually removes that excuse that people give you about not wearing a hearing aid because now with this, it sounded more like natural hearing and hopefully, with this, it can expand the population of people with a mild to moderate degree of hearing loss from not a wearer to a wearer. And if we can do that, and, of course, if we can further expand the other degree of hearing loss, that's great, but if we can simply improve this group of people, we would have significantly and increased our market penetration from whatever we have to add these two times, if not three times more than what we have.

And that I think is the power that low delay processing will give you. You still can understand which with longer delay, but the effort that you need to spend, the finer subtle cues are not there with the longer delay. And that's all I have. I actually did quite well, I was worried that I speak longer than I do, but at least now, I think I have 10 minutes or actually 12 minutes for additional questions, if anyone have, I'll be happy to answer that. But before I wrap up, I wanna thank you for taking the time to listen to me this afternoon and, of course, I want thank all my staff at the ORCA Research Lab that we have set up.

We have Patrick on the far left hand side, who's the electrical engineer and we have Chris the middle who does all the neural science work. And I am the one who stand next to Chris and who's taking all the glory, and they are sweating the whole thing. So I wanna thank them for doing all that and I wanna thank you once more for listening to us. So thank you all very much for listening and I will answer any question if they are, but I would also stop sharing so that you can see a broader screen. There might be a question?

- [Melissa] Dr. Kuk, yes, there is one question in the Q&A 'cause we are short on time. We're gonna have to wrap up right after this. But the question is, would the results shown in the webinar for ZeroDelay processing differ for those who are more severely hard of hearing?

- If these hard of hearing people are not wearing a closed ear mold, the result would be similar, okay? But the issue, of course, is most people with a severe degree of hearing loss would be wearing an occluded ear mold. And in that case, the 10 milliseconds delay, or under 10 milliseconds delay, that would typically find in hearing aids would not really be an issue for anyone. So it would not be an issue for them for those with severe hearing loss.

- [Melissa] Okay, great. I think that's, oh, let's see... Yep, I think we are all set. I'm gonna go ahead and close this down for sake of time today. And I wanna thank you again for joining us for this summit session. We have recorded this course, so if anyone wasn't able to attend, this will be on Audiology Online soon. And we thank you all for joining Dr. Kuk, as always, it's been a pleasure.