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A revised model of noise sensitivity

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Abstract

Earlier definitions of noise sensitivity implicitly presupposed that some sounds can objectively be defined as noise and that some people are intrinsically more sensitive to it. Moreover, noise sensitivity has typically been thought to moderate the relationship between noise exposure and the feeling of annoyance. This cannot be true though, because the experience of sound as noise is subjective. We therefore suggest that noise sensitivity is actually the process whereby a sound is identified as noise. Using semi-structured interviews, this paper presents the results of a qualitative study focusing on the factors related to noise sensitivity, forming the basis of a revised model of noise sensitivity. Study participants were asked to share their thoughts and experiences of being sensitive to noise. Based on their responses, a thematic analysis was used to generate themes related to noise sensitivity. New factors such as masking and perceived control over the sound emerged and were incorporated into the model. The model was also modified by explicitly adopting the terminology 'low road' and 'high road' to describe inputs from the limbic system and the cortex, respectively. The revised model elucidates the potential mechanisms underlying the experience of noise, thereby providing avenues for reducing the level of harm to those who experience it.

1. Introduction

Environmental noise is a population health issue that induces cardiovascular diseases, including hypertension, arteriosclerosis, ischemic heart disease, and stroke (Basner *et al* 2014, Münzel *et al* 2014). Noise can compromise mental health, communication and performance (Berglund *et al* 2000, van Kempen *et al* 2018), as well as affect well-being and health-related quality of life (HRQOL) (Shepherd *et al* 2011), among other negative impacts (Welch *et al* 2023). On this basis, noise is an 'unwanted sound' that is 'perceived as harmful or unpleasant' (Fink 2019, Stansfeld 1992, p 3); in other words, it is annoying.

Initially, noise sensitivity was used to describe a person's vulnerability to noise, specifically, 'the extent of the inter-subject variation in susceptibility to the annoyance caused by noise' (Moreira and Bryan 1972, p 454), susceptibility to noise or sounds, and susceptibility to annoyance from noise (Weinstein 1978, 1980).

Based on this understanding, in 1978 the Weinstein Noise Sensitivity Scale was developed to assess self-reported sensitivity to noise. The scale consists of 21 items regarding attitudes toward noise in general as well as emotional reactions to a variety of sounds (Weinstein 1978). A shortened version of the Weinstein Noise Sensitivity scale has also been developed, consisting of only ten items focusing more on noise sensitivity, with the questions related to noise exposure level removed (Kishikawa *et al* 2006). Subsequently, researchers have defined noise sensitivity as 'a stable trait' amongst individuals (Stansfeld 1992, p 32). Under this definition, noise-sensitive individuals are more likely to focus on a sound and rate it negatively (for example, find it threatening or annoying), and also to have a stronger emotional response to noise, and therefore be less able to habituate to it (Stansfeld 1992, Stansfeld *et al* 1993). People's personality relates to their level of noise sensitivity, with more introverted people tending to report greater sensitivity to noise (Shepherd *et al* 2015).

Noise sensitivity may be defined by outcomes such as health effects that occur in some noise exposed people, but not others. In that framework, noise sensitivity is conceptualised as a factor that moderates the impact of noise exposure (Job 1996). On this basis, noise sensitivity has also been used to predict a number of noise-induced physical and mental health conditions (Stansfeld and Shipley 2015).

The earlier definitions have presupposed, implicitly, that noise can be identified independently of noise sensitivity, and therefore that noise has an objective reality. To avoid this, a system model of noise sensitivity has been proposed in which multiple influential factors determine the probability of a sound being classified as noise (Welch *et al* 2022).

According to this model, noise sensitivity is a process that leads to the evaluation of a sound as noise (Welch *et al* 2022). Firstly, a sound has characteristics that may be detected by the auditory system. If detected, the percept of the sound is processed cortically for meaning, while, in parallel, the information passes into the limbic system where it can contribute to physiological arousal, affect, and wakefulness. Depending upon a person's state, situation, and current activity, combined with their psychological traits and their attitude to the source of the sound, they may interpret the sound as 'noise'. In other words, according to this model, noise sensitivity is not merely a psychological trait. It involves all of the factors related to a person's interpretation of the sound, and is the result of a series of variables and processes that combine to produce it.

The key pathways of noise sensitivity described in the model are consistent with the theory of perception. Specifically, LeDoux proposed that two neural pathways are involved in perception: the 'high road', which refers to the cortical pathway in which people interpret meaningful information; and the 'low road', which is a subcortical pathway, running in parallel with the high road, involving the limbic system, mediating emotional experiences, and linking to physiology (LeDoux 1994, 1998, Pessoa and Adolphs 2010, Ghai *et al* 2018).

In the present study, this system model of noise sensitivity is challenged by exploring people's understanding of noise sensitivity and its influences. To this end, a qualitative methodology was chosen to enable us to expand our understanding of noise sensitivity beyond the existing system model. Semi-structured interviews and thematic analysis were used to provide freedom for both participants and researchers, leading to the generation of themes to be compared to the existing model and to allow for it to be tested and expanded.

2. Methods

Ethical approval for the study was granted by the Auckland Health Research Ethics Committee (Reference Number: AH24576). In total, six adult participants from New Zealand were recruited. Any English speaker over 16 years old without a history of neurological or psychological conditions was eligible to participate. They were asked to share their thoughts and experiences of being sensitive to or annoyed/affected by noise. Recruitment was carried out by posting research advertisements on a University of Auckland webpage. Written informed consent was provided by all of the participants. Data saturation was used to determine the sample size wherein data collection was continued until no new themes emerged from the interviews. Semi-structured interviews were conducted with each study participant via online video link.

Interviews were approximately 90 min in duration, were recorded and were automatically transcribed using Zoom. The researcher compared the transcriptions with the original audio recording and edited them using the 'non-verbatim transcription' approach including the words that were said as part of the dialogue while removing laughter, background noise, verbal pauses, and throat clearing and other meaningless sounds. This method was used to maintain the accuracy of participants' original expressions while retaining the clarity and conciseness of the transcriptions. Qualitative data analysis was conducted to identify, examine and interpret the interview data following a thematic analysis approach (Braun and Clarke 2006). Firstly, initial codes representing features of the data were identified, categorising and grouping similar codes to generate themes with quotes to support each assertion. Subsequently, themes were described and the findings interpreted.

The researcher JW conducted the interviews and completed the transcription checking, editing and primary coding of the data. Researcher DW reviewed the codes to corroborate them. The research team DW, KD, DS and JW reviewed the themes together for suitability and explored the themes and subthemes to identify ways in which they could be better described or categorised. These themes and codes were validated through the consensus of the research group. NVivo (Release 1.7) software was used to conduct the coding and to label the themes.

3. Results

All six participants recruited (two males, four females) were adult English-speaking residents of New Zealand who lived in Auckland City, the largest of New Zealand's cities, with a population of approximately 1.5 million.

Four main thematic areas capture the process that occurs when a person hears a sound. The first area (called the 'acoustical signal') is related to the physical sound itself, including sound qualities and sound quantities. The second area (called the 'perceptual process') consists of factors related to a person's sensation and perception of sound, the process of how a sound signal is heard by a person and is then integrated to form their understanding or affect their state, and ultimately influence a person's perception of the sound and form the evaluation of a sound as noise. The third area (called the 'interaction between sound and person') is a factor that depends on both the acoustical properties of the sound and the person's perceptual experiences as a result of it, such as the relative sound level between different sounds and the masking of desired information by extraneous sounds. The fourth area (called 'related constructs') refers to the separate processes that govern the decision about whether a noise is annoying.

3.1. Acoustical signal

The acoustical signal section includes the factors regarding the objective characteristics of a sound itself, such as sound quantities and sound qualities.

3.1.1. Sound quantities

Quantities are the basic physical/acoustical aspects of a sound that are measurable, for example, the level, the frequency, the spectral energy, the exposure duration, and the proximity to the sound source.

3.1.1.1. Sound level

The first aspect under 'sound quantities' is the sound level which tends to correlate with the perceived loudness. A high level or loud sound could be regarded as noise:

> *'If it is random noise or above a particular dB threshold, then it becomes unpleasant.'*

> *'The same music, if it is played too loud, then it becomes a noise.'*

On the other hand, there was also a theme where a soft sound could also be considered to be noise:

> *'Like I heard a little…this like kind of the soft sound, so not really like the sound that is very loud, you know, like for example cars, I can more handle that, but… the beeps or the electricity or like a little noise on the background, but it's kind of annoying.'*

Participants also reported that a soft sound could be even more irritating than a louder one:

> *'It's more really like the, yeah, the backgrounds, like that is kind of more irritating me than obvious sounds, like yeah.'*

When asked about why they did not like quiet sounds, people seemed uncomfortable with the sense that they could hear them but could not listen to them clearly:

> *'So it's kind of, you know, you hear it, but you don't know. So I think it is more, yeah, it's more annoying. And if it's hard sound, it's kind of okay, you know…'*

3.1.1.2. Sound persistence

Another theme within sound quantity related to the sound's persistence; if a sound was relentless, it could lead to some discomfort and was more likely to be treated as noise:

> *'If it's just a passing sound, I think the amount of emotion I feel is much less. About something where the unexpected noise is lasting longer, then more feelings will start to come up… a feeling a bit shaken or surprised, and then…frustration about the loud noise.'*

Moreover, when exposed to sound over a significant period of time, a sense of tiredness might also make people judge a sound as being annoying:

> *'When you're exposed to loud sounds over a long period of time, it can lead to… you can get mentally and physically tired… as the noise gets prolonged, I need to move away. I need to go to a place where it's quiet.'*

For sounds that are persistent, if a sound has breaks in it, it is seen as providing respite for the listener and are less likely to be considered to be noise:

> *'So if it is noise, and then there is a break, and there's noise, and then there is a break, that's fine. But if it is prolonged the noise, then hmm. So it's time. It's getting more, and the sensitivity is getting more. You get irritated more.'*

3.1.1.3. Proximity to the sound source

The third theme within sound quantities was the proximity of the sound source to the listener, with the closer the sound, the more likely it was to be regarded as noise:

> *'Yeah, if I feel it is closer by, if it's more closer to… and then it's more annoying…I would be less bothered because I know it's further away…'*

3.1.2. Sound qualities

These are defined as aspects of a sound that are objectively present but not captured in time/frequency-weighted averages, though they are apparent to listeners, such as the way sound is structured over time:

> *'It's okay if it's like constant noise, like a fan going or something. But yeah, if it's too like inconsistent in volume and like stuff like that, then yeah* [that would be annoying]*.'*

> *'A sound that is repeating, that is continuous, but like doesn't go away. Um, I think, yeah, what is the most annoying is it's repeated, so it's like you know it comes and goes, but you know it's coming back. The sound so it's like not temporary, it is something that comes that repeats itself.'*

3.2. Perceptual process

The second thematic area relates primarily to the internal processes of a person's body and mind. When a sound is detected, it can inform a person's understanding and contribute to their state. This, combined with their personal components, as well as some situational components, influence a person's attitude to a sound, potentially leading to it being considered noise.

3.2.1. Sensation

Sensation refers to an auditory system detecting and transducing a sound signal into neural activity. People's sensations of sound can be different and are the precursors of perception.

> *'Sometimes I feel like I might hear it, but maybe other people don't even notice, you know … I always, you know, like when I complain about 'can you hear?'… it doesn't bother them that much.'*

3.2.2. Low road

When we hear a sound, it is processed in part through the low road and contributes to our reflexive responses. These emotional responses (e.g. anxiety and worry) and physiological responses (e.g. increased heart rate) may lead the sound being perceived as noise:

> *'Probably quite anxious and worried that something has happened…like heart beats fast, maybe a bit of hand sweating.'*

Since the low road is subconscious, and occurs at a faster rate than the high road, its responses feed into the process of 'evaluation of the sound as noise' in the high road. Information about sound passes through the low road in parallel with the high road and can influence a person's state, with the state then interacting with the evaluation.

Moreover, for a salient sound, the psychophysiological responses in the low road can also influence the sensation and the 'attention' component of the high road. If a person is worried, nervous, or alert, they may start noticing sounds more. People's attention could also be captured by the sound automatically, then they may get information from it, and the high road process starts.

3.2.2.1. State

This refers to a person's psychophysiological state, including their state of emotion, etc.

A person's pre-existing state may influence their attitude to a sound. In this theme, the pre-existing state increases sensitivity:

> *Like for noises, or like bird sounds, yeah, it depends on moods, but also like, lack of sleep, Yeah…like, not long ago, because I was so tired, and then I felt probably also because of like the stress, and then it was full moon as well. So I think it made me more kind of frustrated and annoyed by it. But I think also more sensitive.'*

People's state may also affect sensation, such as if they are worrying, feeling upset, nervous, or angry, they might be alerted and notice other sounds more easily:

> *'Like for noises…it depends on moods…and then I felt probably also because of like the stress…So I think it made me more kind of frustrated and annoyed by it [sound]. But I think also more sensitive, like to sound and also to like this background noise.'*

> *'When I'm like trying to go to sleep, or when I need to focus, like I'm in an exam, feel like much more like aware of what's going on around me. And like noises that wouldn't otherwise be an issue.'*

On the other hand, sound can also induce a person's psychophysiological responses, and affect their state:

> *'During Chinese New Year celebrations, we set off long strings of fireworks as part of the celebration… And even though it's a controlled environment, and you know what's going on. You always do feel your heart and the breath and nervousness…'*

Three kinds of psychophysiological reactions may be induced by a sound, namely affect, arousal and wakefulness (Welch *et al* 2022). These are all mediated via the low road and constitute a person's state. In this research, we verified the themes of 'affect' and 'arousal' and elaborated on them separately, as described below. Wakefulness can be influenced by sound differently when in a state of full wakefulness compared to during sleep.

3.2.2.1.1. Affect

Affect refers to emotional responses to sounds caused directly by a sound. When a person hears a sound, they may immediately feel unpleasant emotions as a result, and therefore regard the sound as noise:

> *'Maybe you're in this particular space and someone dropped something loud, then maybe then, yes, I would feel …anxiety and nervousness, but probably very momentarily.'*

3.2.2.1.2. Arousal

This refers to both physiological arousal via the autonomic nervous system and being aroused from sleep. People may describe it as a sudden physical response to a sound:

> *'Like this morning at like 9.30, the fire alarm went off. They did a test, but it was really sudden…Yeah, the only big symptom I can think of is just like the heart beating out of your chest, or like feeling like your stomach has dropped.'*

> *'When people wake up and go to the toilet … if I'm already awake, it's fine. But if I'm, for example, sleep deep and sleep and they do it like at five in the morning, it annoys me.'*

3.2.3. High road:

Through the high road, people convert sound signals into meaningful information and form their unique understanding of the signals. This starts from people's sensation and then follows the steps of attention-information-interpretation-evaluation of the sound as noise. For example, if someone is talking, we may listen and extract information from that sound signal; and if the information in the sound is somebody saying, 'Try to calm down', the interpretation would depend on how one was feeling at the time—if one was feeling upset, it might upset one more because the message may be interpreted as patronising and disrespectful. On the other hand, if one was feeling relaxed already, it might relax one more, because it may be interpreted directly as a helpful reminder. So, a person's interpretation depends on how they understand the information. Then, based on the interpretation, an evaluation of whether the sound is noise can be developed. Multiple factors fall within the process of evaluation, and these are explained in the section on 'Evaluation of the sound as noise' below.

Generally speaking, when people perceive a sound, they pay less attention to the sound itself than to the meaning behind it:

> *'But I guess, again it comes down to the content rather than the actual noise itself…*
> *I think for me, the way I sort of approach the situation is to try to understand what the noise is.'*

3.2.3.1. Attention

Attention is the process that modulates conscious awareness and which prioritizes certain information at the expense of other information (Noyce *et al* 2023). Acoustic attention can come from people focusing on a sound volitionally, which can affect the high road, make people aware of the sound, and may lead to them considering it to be noise:

'Like, because I charge my phone usually during the night… then if I pay attention, I hear the noise.'

On the other hand, attention can also manifest as bottom-up automatic responses to salient events (Noyce *et al* 2023). An unusual sound may capture a person's attention, evoke psychophysiological responses via the low road, and then be considered noise:

'When I hear a sound very loud, it's kind of very unnatural… it needs attention … that makes it more scary, I think.'

Furthermore, if a person wants to focus on something, but a sound captures their attention, they may think the sound is intrusive and consider it to be noise:

'I could be playing music for the entire day like really loudly in my headphones, but when it comes to like I'm in bed, or I need to do work, it won't even be like nice to listen to at all. It will just be like so annoying because I can't focus on what I want to focus on, because that's all I can pay attention to.'

3.2.3.2. Information

The information contained in a sound (e.g. the content of speech) may affect a person's attitude toward a sound. For example, someone complaining may be more likely to be considered noise:

'I don't like the sound of complaining, anyway though…I don't want to necessarily have to worry about this incoming noise that is inherently negative.'

3.2.3.3. Interpretation

Interpretation is the process people go through with incoming information to extract personal meaning from a sound. For example, people may have different interpretations of some sounds, such as laughing and crying:

'So, it is a different sound from a gurgling, laughing and talking sound like a baby crying… You would want to do something about it to stop the child from crying. Whereas you wouldn't want to stop a child from laughing and gurgling and, you know… you love to hear that sound.'

People enjoy the laughing sound a baby makes, as they may interpret it as the child being happy, whereas a crying sound can be interpreted as the child being in distress. These different interpretations give different meanings to the sounds, and this may influence the likelihood of them being interpreted as noise:

'…Because you don't want to see… a child being in distress, the very fact the child is crying. That means he or she is in distress and needs something… Whereas if a child screams and cries all day, that can be discomforting.'

3.2.3.4. Evaluation of the sound as noise

The evaluation of the sound as noise captures how people feel about the information they get from the sound and how they judge it.

With the information obtained from a sound, an evaluation of the sound can be made. We found that the process of evaluation was quite complicated: though hearing the same sound signal, different people may understand and consider it differently. The themes related to the 'evaluation of the sound as noise' fell into two groups with a total of ten subfactors that could influence the process of evaluation. The first group consists of situational components which include perceived control, perceived congruence, perceived necessity, and unexpectedness; the second group consists of personal components, including memory, associations, attitude to the sound source, perceived risk, desired behaviour and psychological traits. People generate their unique understanding of a sound based on one or more of these factors.

Situational components: The situational components are factors that can influence attitudes to a sound depending on the context.

3.2.3.4.1. Perceived control

the sense of control a listener has over a sound. If a person cannot control a sound to which they are listening, they are more likely to consider it to be annoying:

'I don't like if I'm on the bus and somebody has like a speaker, and they're playing really loud music that might annoy me.'

Perceived control of a sound can make a person feel more comfortable, and their attitude toward a sound could change, even in response to the same sound:

> *'But if I'm on the bus, and I have my headphones in, and I can play my own really loud music, like the same volume, but I can like play it in my earbuds, and I know that I can just turn it off if I need to, then I won't be annoyed by it at all, even if it's the exact same song.'*

3.2.3.4.2. Perceived congruence

If people think a sound is unsuitable or improper, they might consider it to be noise:

> *'So if my neighbours are having a loud party, say once a month, I will be accepting, but if they're having it every day for 24 h, then it won't be acceptable.'*

In addition, 'perceived congruence' could also mean the extent to which a sound is appropriate in a particular situation:

> *'I would say a good example is a rubbish truck coming to empty the red or blue bins, recycling rubbish happening when a person is up and about, so maybe after 7 or 8 am, that would be fine, but if that happens earlier than that or late at night, it maybe changes the emotional response.'*

3.2.3.4.3. Perceived necessity

People are more likely to regard unnecessary sounds as noise. For example, when other people complain about trivial things, it would be considered unnecessary, and then evaluated as 'noise':

> *'I think that, yeah, it depends on the meaning. If I can like hear people talking and like one person is complaining, and it's about something really like trivial. …Then I would probably be quite annoyed by the like incoming voice. I couldn't get away from it.'*

On the other hand, people can accept a sound which is considered more necessary or useful to them. This 'perceived necessity' can change their perception of the sound:

> *'But if I could hear people complaining and it was about like something really bad… I wouldn't like get annoyed by that, because it's like, well, you know, a reason to complain. I would be complaining as well, you know.'*

The perceived necessity of a sound also means that if a sound is unavoidable, it is not evaluated as noise:

> *'I think I can accept noise up to a certain level, if it is necessary, like if some work is being done in my house, and there's a loud noise, I can accept that with a good reason…'*

3.2.3.4.4. Unexpectedness

If people do not expect a sound, they might feel fear or surprise when suddenly exposed to it:

> *'Like if I'm in my room … and then, all of a sudden, there's a like a really loud alarm …that will like scare me.'*

Sometimes, the unexpectedness of a sound might also mean a person did not intend to hear it. Thus, these unexpected sounds are likely to be regarded as noise:

> *'I think also, what might determine whether I find it pleasant or not is whether I'm intentionally listening to it … It's unexpected, that means you don't want to.'*

Personal Components: Personal components are personal characteristics or experiences that influence the evaluation of a sound.

3.2.3.4.5. Memory

A person's memory of a previous experience of a specific sound may affect their future judgement of the same sound. For example, if a person has had some unhappy experiences with TV sound when they were very young, they may dislike the sound of TV and consider it to be noise:

> *'I went to bed early because I was little, and then my parents would stay up and watch TV, and I used to be so like aware of the TV noise, and it would really annoy me because I would hear like every single word.'*

And having formed attitudes, memory may cause those attitudes to persist:

> *'I would say, actually, yeah, that is still the same…the TV still kind of annoys me… So I guess I've always been annoyed by the TV sounds going on.'*

3.2.3.4.6. Association

There may be learned associations with particular sounds that predispose their evaluation of a sound as noise.

People may associate a particular person's tone or voice with an inherent feeling:

> '*… I've learned to associate what she has to say, you know, like this will be like interesting, or this will be like cool or exciting…but with this one friend, in particular, it was a completely different context… I think that would quite annoy me, just hearing her like tone and voice.*'

A particular sound may also be associated with a specific mood. For example, a siren may make a person feel uncomfortable and therefore be evaluated as noise:

> '*I think just, um, we are conditioned to link those two together. Every time we hear a siren, we think of emergency, which makes our body react in that way.*'

A sound associated with bad feelings or a negative mood is more likely to be considered noise.

3.2.3.4.7. Attitude to the sound source

A listener's pre-existing attitude towards the perceived sound source may influence their judgement of a sound generated from that source. For example, if we dislike someone, we might not want to listen to what they are talking about:

> '*For example, you know, like when, for example, coaches…like yelling at people, and I think if I don't like the person, then it might… it makes it more annoying to listen to it'.*

On the other hand, a person who is liked may be evaluated more positively:

> *'And I think if I more respect the person, and it's maybe more acceptable to listen.*'

3.2.3.4.8. Perceived risk

People's pre-existing thoughts, such as health knowledge about sound, may influence a person's consideration of sounds with respect to the potential harm they might cause and result in a desire to avoid it:

> '*You know that the side effects of being exposed to some* [noise] *it is just like alcohol and smoking. You know the danger is the side effects of being exposed to noise, or you know, noise over a long period of time.*'

This theme is reflexive: awareness of the risks of noise to health may lead a person to being more sensitive to it than had they been unaware of the risks.

3.2.3.4.9. Desired behaviour

If a sound prevents or interferes with what a person wants to do, it is more likely to be considered annoying.

> '*When I'm like trying to go to sleep or when I need to focus…I feel like much more aware of what's going on around me. And like noises that wouldn't otherwise be an issue… it's like really noisy, or something that might work towards annoying me further.*'

3.2.3.4.10. Psychological traits

Psychological traits could affect a person's perception. A theme emerged that some psychological traits were seen as being linked to noise sensitivity:

> '*I think definitely it's linked to psychology… Sensitive people, I think that if there is a distinction, I think maybe also more introverted people than extroverted people.*'

> '*I'm a bit more impatient. So possibly, that leads to me being a bit more sensitive to noise.*'

3.3. Interaction between sound and person

There are factors relevant to both sound and person and the interplay between them. When a person hears sounds together, one may mask another, and the masking can affect the person's sensation and evaluation of the sounds.

3.3.1. Relative sound level

This refers to the effect of different sound levels between the sound people want and other sounds. If a person is doing something quiet (e.g. reading), their auditory system adapts to low sound levels, so other sounds are more likely to be noticed and perceived as noise. In contrast, if the self-generated sound (e.g. talking or watching TV) is loud, the listener adapts to high sound levels, so any low-level sound is not as obvious, and is therefore less likely to be experienced as noise:

> *'For example, if I read a book, it* [the background sounds] *might be more annoying, because …* [of] *all the sounds in the background. But, for example, if I watch a movie or call someone, you know … I probably won't be bothered that much with it…*
> *Because if I watch a movie, there are a lot of sounds, so it's kind of that is more getting my attention because the sound is loud. Yeah, it's more pleasant.'*

3.3.2. Masking

Masking is the ability of one sound to decrease the audibility of another sound (Emanuel and Letowski 2009). Masking can occur at a peripheral level either due to masker excitation of the inner ear causing adaptation or activation of the auditory nerve such that a signal is no longer as easily detectable, or the suppression of the cochlear active process to the signal (Delgutte 1990).

Alternatively, masking may occur centrally in the brain due to the perceptual interference caused by the masking sound on the signal, known as informational masking (Wilson *et al* 2012, Tuomainen *et al* 2024).

When two sounds arrive at a listener together, the sound with the greater intensity has a bigger masking effect on the other. Based on this, a background sound can mask the sound a person wants to hear and then be considered as noise (e.g. talking or watching TV):

> *'I don't like loud music because I can't talk to people. Because the music is so loud, I have to speak above the music. People can't hear me talking.'*

> *'Sometimes, when I go to a wedding, and I'm standing very close to the stage or very close to the speaker, I cannot engage in any conversation because that noise is interfering with communication.'*

In this case, the sound from the stage has a greater intensity than people's talking sound and, therefore, has a bigger masking effect on their conversation than the other way around. The signal that people are trying to hear is masked by the background sound, and people are likely to consider these background sounds as noise.

Masking sounds may be perceived as noise for two reasons: the direct effect of not being able to hear the desired sound; and the secondary effect due to the awareness of masking.

Masking effects may also be perceived positively, when a masker is used to reduce the annoyance caused by noise, such as playing music to mask noise from a neighbour.

3.4. Related constructs

Noise annoyance and loudness are constructs that are related to the process of noise sensitivity; though they are not part of the process. Noise annoyance can only occur if a sound has been evaluated as noise, and is associated with stress and systemic harm caused by noise. Loudness is a separate perceptual phenomenon that is related to noise sensitivity because sounds of higher levels tend to be perceived as louder, as well as being more likely to be evaluated as noise.

3.4.1. Noise annoyance

Noise annoyance describes the state of mind that leads to the negative effects of noise. In order for noise annoyance to occur, a person must first have evaluated a given sound as noise through the noise sensitivity process. For most people, the distinction between those two processes is not made.

> *'Traffic*[sound] *I find quite annoying. Yeah, I call that noise.'*

> *'I call that noise because… it doesn't put me in a good mood. It's just a bit annoying and distracting.'*

3.4.2. Loudness

Loudness is a percept that is related to sound level.

If a sound is not evaluated as noise, even if it is at a high level, it will not be considered as noise (e.g. loud music at a concert); whereas another sound which is unwanted, may be evaluated as loud and as noise, even if it is at a lower level.

> *'So when I do listen to loud music or louder volumes, it's either with good headphones on, that actually sounds pleasant, and it's not too loud… maybe I'm walking and someone drives past and they have loud music playing. It's unexpected, that means you don't want to.'*

3.5. Relationship among the components

In summary, all of the components described above are related to the process of judging a sound as noise or as being annoying or loud. These components are not independent of one another. When people consider a

sound to be noise, it is not only because of the sound itself but also about how a person evaluates it under different situations, as well as the listener's personal characteristics such as their memory or personality traits. These components always work together:

> *'I think, you know, the context and the person both like work together. You can't just have one or the other. They sometimes work like in different balances.'*

> *'It's not like different particular sounds will always trigger me. No matter what time of the day it is. It depends always on the environment that I'm in, or like the day that I've had that kind of thing, or who I'm with.'*

In different situations, different people might mention different aspects of the overall model as being more influential. For example, in this quote, the participant mentioned that 'unexpectedness' and 'perceived congruence' were probably more influential in some situations when considering a sound to be noise:

> *'I think it's very important to me as reading the context and thinking about why people act in a certain way…*
> *If I'm not expecting the noise, or if I don't think it's suitable for the environment, I think that's when I'm particularly sensitive to it. It doesn't matter what it is.'*

Similarly, the extent of 'perceived control' was stressed by a participant in another case:

> *'I don't like if I'm on the bus and somebody has like a speaker, and they're playing really loud music, that might annoy me. But if I'm on the bus, and I have my headphones in and I can play my own really loud music like the same volume… and I know that I can just turn it off if I need to, then I won't be annoyed by it at all, even if it's the exact same song.'*

> *'… If I had the control, I think I would be okay with that.'*

However, no factor works independently. Aspects in the model work together to determine individual responses to different sounds.

4. Discussion

The findings reveal that the components of noise sensitivity, and the two high- and low-road pathways within them, support the previously proposed 'System Model of Noise Sensitivity' (Welch *et al* 2022). In the present study, these have been extended to include new aspects and sub-factors (figure 1).

In the diagram, each circle represents an aspect of noise sensitivity (a factor); and the final judgement of 'the sound as noise' is the result of all of the factors. The arrows between the factors show the direction of the processes, with the heavier arrows representing the two main routes associated with sound perception: the high road and the low road (LeDoux 1994, 1998). When people detect a sound, information about the sound will pass through the high road, be interpreted and then be evaluated. In parallel, and more quickly, the sound stimulus will also cause activity in the low road, and contribute to a person's arousal and affect to influence their psychophysiological state, which in turn contributes to the evaluation process. Since the low road is faster, the response of the low road can also direct a person's attention and then influence the high road. All of these also depend on situational and personal components through the listener's evaluation process. Hence each person's 'noise' might be different, and everyone makes their own judgement about whether a sound is noise or not. Furthermore, masking and the relative sound level may affect sound sensation and then influence both the high and low roads.

Different shadings are used to show the layers of the factors: the black circles (the first layer) represent the factors associated with the main pathways from sensation to evaluation of the sound as noise; the grey circles (the second layer) represent aspects of the first layer; and the white circles (the third layer) are the sub-factors of the second layer.

4.1. The difference between the revised and previous model of noise sensitivity

In the previous version of the System Model of Noise Sensitivity (Welch *et al* 2022), the 'sound source' was treated as the starting point. In the current model, this has been changed to 'attitude to the sound source' as one of the sub-factors of 'evaluation of the sound as noise', because the 'sound source' in itself does not influence a person's judgement, but rather it is their attitude to the source.

Regarding sound sensation, in the previous model, there was a factor called the 'auditory system', which included the ears, the peripheral auditory pathways and the primary auditory cortex, and the next element, called 'meaning', considered to be a generalisation. In the new model, these processes have been analysed more and explained in more detail. Furthermore, at the level of sensation, two new factors ('masking' and

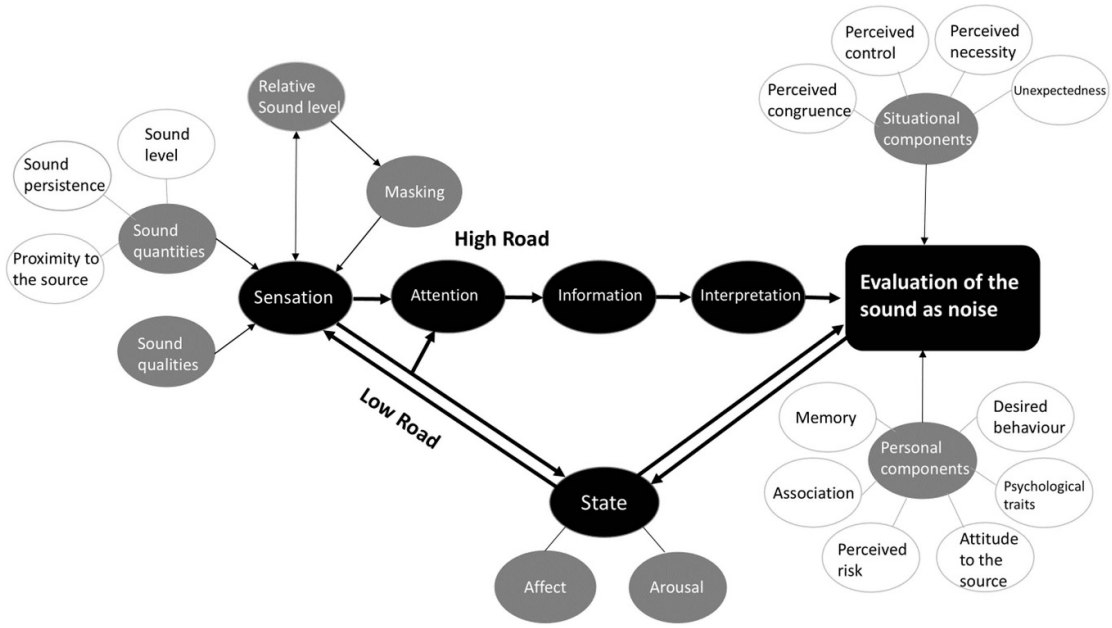

Figure 1. Revised system model of noise sensitivity.

'relative sound level') have been introduced. These are key factors leading to the experience of noise and were not clearly expressed in the earlier model, so have been made explicit in the revised model.

For 'sensation', the revised model separates the information into parallel 'high road' and 'low road' pathways to illustrate the two main processing pathways that lead to meaning in the brain. The low road includes factors such as 'arousal' and 'affect', that are part of a person's state. The low road is similar to the factor called the 'limbic system' in the previous model, and extends upon it. The 'low road' is considered to be a better name to indicate that it is a subcortical pathway that runs in parallel with the high road. The factors of state, arousal and affect remain the same as in the previous model. The previous model included a factor called 'wakefulness' as part of the section called 'state'. This has been reconsidered because if a sound exposure occurs during sleep and causes a transition from deeper to lighter sleep stages, this is an unconscious process which is not related to noise sensitivity (Dang-Vu *et al* 2010). As such, the factor 'wakefulness' was not included in the revised model.

The single factor 'meaning' in the previous model was broken into different steps in the revised model, namely into 'attention', 'information', 'interpretation' and 'evaluation of the sound as noise', to better illustrate the process of how people form their conscious understanding of a sound.

A total of ten sub-components were identified in relation to the factor 'evaluation of the sound as noise', which may all influence a person's understanding of a sound. These were divided into two groups, namely 'situational components' which depend on the context, and 'personal components' which relate to aspects of the listener. Within the group of situational components, the factors of perceived control, perceived congruence, perceived necessity, and unexpectedness are included; and the personal components contain the factors memory, association, attitude to the sound source, perceived risk, desired behaviour and personality traits. Among these, 'attitude to the sound source' and 'personality traits', which were single factors in the previous model, were considered to be part of personal components that contribute to the 'evaluation of the sound as noise' in the revised model.

The two boxes 'situation' and 'current behaviour' appeared around the endpoint 'the sound is noise' in the previous model. These two factors are now captured by the situational and personal components that contribute to the 'evaluation of the sound as noise', elaborating more specifically on how these contextual factors are connected with a person's perception.

Finally, rather than the previous model's endpoint of the decision 'the sound is noise', in the new model, 'evaluation of the sound as noise' has been used as the endpoint to represent the perceptual process. In this process, when people attend to and become aware of a sound, first they get information from it, interpret the information, and then consider it with the current situation and, in combination with their personal traits, and psychophysiological state, form their evaluation, that the sound either is, or is not, noise.

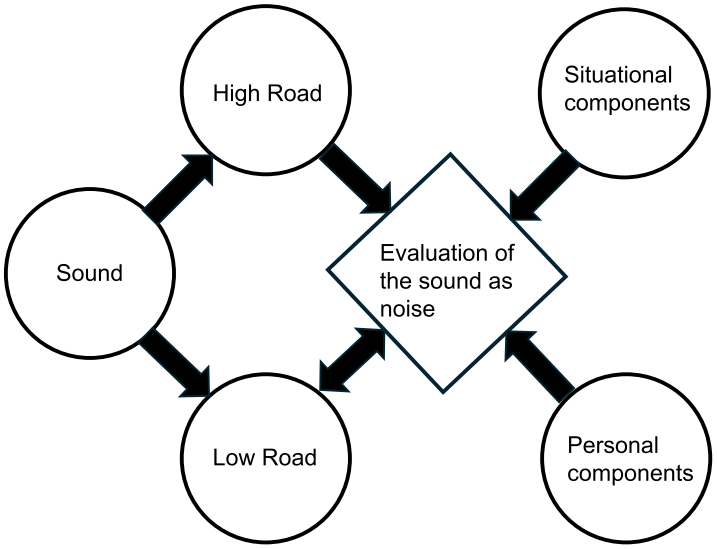

Figure 2. Simplified version of the revised system model of noise sensitivity.

The system model of noise sensitivity shows in detail how a sound is evaluated as noise. To clarify the main inputs of the evaluation of sound as noise, a simplified version of the new system model is provided (figure 2).

When a person detects a sound, there are five main inputs that may affect their evaluation of whether a sound is noise: the sound itself; the high road, which represents understanding; the low road, which represents the psychophysiological state; the personal components, which are intrinsic to the individual, and situational components, which relate to where a person is and what they are doing. These inputs interact in the evaluation of the sound, and if the evaluation is negative, the sound will be perceived as noise.

4.2. Application of the system model

The model depicts each factor in a bubble with links to other factors, and it is these interactions that make a person more or less sensitive to a sound as noise. Below are two examples to illustrate how they apply in the real world.

Example 1: If a person is reading a book quietly at home while someone starts mowing the lawn outside, the person might be more sensitive to the mowing sound being noise. The noise sensitivity process for this scenario would be as described step-by-step below:

Sound qualities (sudden onset of a lawnmower motor and slow fluctuation over time) Sound quantities (a high sound level)

Sensation (hear the mower as having a relatively high level compared to the quiet room)

Attention (captured by the sound)

Information (lawnmower motor sound)

Interpretation (someone is mowing the lawn outside)

Situational components:

- Perceived congruence (not congruent because the listener was reading quietly but now there is a loud sound)
- Perceived control (no control over the sound)
- Perceived necessity (lawns do need to be mowed)
- Unexpectedness (this would depend on the time of day)

Personal components:

- Desired behaviour (is reading)

Evaluation of the sound as noise (the sound is obtrusive and unpleasant)

For the situational components, since people might think of a situation from different angles, all of the possible relevant components are listed. However, in reality, not every situation would involve every component. There would also be a low road process occurring simultaneously.

The steps before sensation are the same, so we started from sensation and to 'evaluation of the sound as noise' to show the low road process:

Sensation (hear it)

State (listener may be startled by the sudden sound- Affect; or feel the heart beating fast—Arousal)
Evaluation of the sound as noise (the sound is unpleasant)

The state changes in the low road may also direct a person's attention and reinforce the high road process in this case.

Example 2: If a person is trying to go to sleep in a hotel in a busy city and is scared up by a sudden loud car horn outside. The car horn could be considered to be a noise for the person, and the relevant factors and the process of the noise sensitivity would be as below.

First, the low road process would happen:
Sound qualities and quantities (a car horn sound at a high level)
Sensation (hear it)
Arousal
State (being scared)
Evaluation of the sound as noise (the sound is annoying)

In this case, if the horn sound lasts sufficiently long, the person may also start to attend to it and become aware of it. Then, the sound would also be evaluated via the high road. The process would start from the state of arousal:

Attention (the loud sound captures the person's attention autonomically)
Information (horn sound outside)
Interpretation (someone is honking the car horn late at night)
Situational components:
Perceived congruence (people are trying to go to sleep but there is a loud sound)
Perceived control (no control over the sound)
Perceived necessity (driver needs to use the car horn in sudden situation)
Unexpectedness (car horn is not common at night)
Personal components:
Desired behaviour (want to sleep)
Evaluation of the sound as noise (the sound is disturbing and unpleasant)

The evaluation that 'The sound is noise' involves many factors through either one or both pathways. Based on this theory, whether or not a person perceives a sound as being noise is ever-changing. If any one factor in the process is different, the result might not be the same. In Example 1, if the person stops reading and starts watching television, the person may no longer consider the mowing sound to be noise if the lawnmower is masked by the television, or the television's sound level is so high relative to the lawnmower that the latter is no longer obvious.

The impact of noise on health can occur either through sleep disturbance or through subjective perception and the emotional response to a sound (Münzel *et al* 2014). The revised system model of noise sensitivity focuses on the subjective perception of noise and excludes sleep disturbance as being a separate process. Moreover, our theory reveals how perception and emotional response influence a person's sensitivity to noise.

4.3. Strengths and limitations

The study's strength is its qualitative research approach, a way of gathering deep ideas from people and gaining a more complete understanding of psychological concepts. It took our earlier model of noise sensitivity as its starting point, and findings revealed new factors and provided insights into noise sensitivity. The detailed descriptions of participants' experiences, feelings and thoughts helped to generate new ideas and uncover new factors contributing to noise sensitivity. In addition, the flexibility of the semi-structured interview approach provided good opportunities to probe into each participant's experience of noise in their lives, allowing for the piecing together of a more complete story.

The qualitative approach also has limitations. The findings rely on the researchers' interpretation and analysis of the data, so are subjective, though the use of quotes as evidence to support the presence of a theme mitigates this. Participants had difficulty in describing two aspects of noise sensitivity. One was the factor 'sensation': people have limited insight into their own hearing or when they become aware of a sound because these processes are subconscious, so the interview approach did not allow data relevant to this to be captured; the other was the factor 'psychological traits', which require specialized vocabulary to describe, whereas participants could only use lay terms and therefore struggled to provide responses of relevance.

4.4. Future research and work

Future quantitative measurements would be helpful for assessing the components of the model. One approach could be to divide the model and develop different approaches for each part. For example, for the factors associated with the evaluation of a sound, verbal data collection could be useful. Sounds could be

presented and people's thoughts or attitudes captured via questioning. With respect to states, since they relate to people's physiological and emotional responses when hearing a sound, physiological measures such as blood volume pulse, heart rate, and skin conductance can be used, and existing rating measures could be applied for the emotional assessment. For the factors regarding the interplay between sound and person, such as masking and relative sound level, experiments could be conducted using sounds across different frequency ranges and levels to see whether and when a sound would be considered noise. Simulation with different situational variables might also be a useful approach.

In addition, the correlations between the factors of noise sensitivity, such as sound level, and the responses people could make due to it, such as annoyance, could also be analysed to provide a broader understanding of noise sensitivity and its influences.

In the future, researchers could test the theory by using socio-acoustic surveys to investigate noise annoyance and perceived noisiness, or by separating specific noise sources such as traffic noise and ambient noise.

This research provides new perspectives into understanding why people respond differently to sound. The health effects of noise result from a complicated system, which means that besides noise control, there may be alternative means to prevent adverse consequences. If exposure to a sound over a period of time is unavoidable, consideration of the other factors may be helpful. For example, in conditions where there is unavoidable sound from outside, a person could make the decision to listen to music or talk with friends, rather than trying to sleep or read quietly. In that case, the relative sound level and perceived congruence contribute to making a person less likely to consider the sound as being annoying, so the adverse effects of the sound on health may be reduced.

This new approach might also provide broad ideas for public health policy related to noise exposure—each factor in the system model of noise sensitivity presents a possible intervention point to prevent adverse effects of noise on health. Sound source monitoring and reducing the sound level are traditional approaches for coping with noise (Berglund *et al* 2000, Kim and van den Berg 2010). The protective effects of this are focused on the single intervention point of 'sound quantities', which means many more ways could be explored to deal with problems in noise. Besides, the new model may provide intervention points that are more individual, such as interpretation and evaluation. For example, if road maintenance work is required, though the sound cannot be changed, the intervention points might be 'unexpectedness' and 'perceived congruence'; providing the neighbourhood with a timetable of when loud sounds could be expected, and an explanation about the necessity of doing the work would help people to understand and accept it.

Furthermore, awareness of this model may be helpful for noise-sensitive people, and talking about noise sensitivity may help people to re-evaluate themselves. This model shows people that their sensitivity to noise is not some individual 'fault', rather that it depends on many factors, and they might have more control over it than they think. In the future, the model could be used to treat noise sensitivity. Audiologists could use it to conduct health consultations, and the model could also be considered as a tool for cognitive behaviour therapy. Through talking about noise sensitivity, people can break it down into components and then identify issues more concretely. Acquiring a complete understanding of noise sensitivity may also help change a person's thinking patterns and alleviate the effects of unwanted sound.

5. Conclusion

A more comprehensive understanding of noise sensitivity has been gained, including the range of implicated factors and how each of these factors work together. There is a need for approaches to be able to measure these constituents of noise sensitivity. In the future, we hope to develop measurement methods to test them, investigate the extent to which each element could affect noise sensitivity and whether there are different weightings associated with them. Improved understanding could lead to the identification of ways of coping with noise issues. Noise control could be helpful in some aspects of sound; however, more diverse and individualized approaches could be developed to address the many different aspects of noise sensitivity.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Declaration of interest statement

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