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RESEARCH ARTICLE

Perceived biodiversity: Is what we measure also what we see and hear?

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Abstract

1. Biodiversity is crucial for human health and well-being. Perceived biodiversity—people's subjective experience of biodiversity—seems to be particularly relevant for mental well-being.
2. Using photographs and audio recordings of forests that varied in levels of biodiversity, we conducted two sorting studies to assess how people perceive visual and acoustic diversity and whether their perceptions align with species richness and proxies for forest structural diversity ('actual diversity'). Per study, 48 participants were asked to sort the stimuli according to any similarity-based sorting criteria they liked ('open sorts') and perceived diversity ('closed sorts').
3. The main perceived visual forest characteristics identified by participants in the open visual sorts were vegetation density, light conditions, forest structural attributes and colours. The main perceived acoustic forest characteristics identified in the open acoustic sorts comprised bird song characteristics, physical properties such as volume, references to the time of day or seasonality and evoked emotions.
4. Perceived visual and acoustic diversity were significantly correlated with actual visual and acoustic diversity, respectively.
5. We further computed several objective visual and acoustic diversity indices from the photos and audio recordings, for example, a Greenness Index or the Acoustic

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Complexity Index, and assessed their relevance for perceived and actual diversity. While all acoustic diversity indices were significantly associated with perceived and actual acoustic diversity, for the visual sense, the Greenness Index successfully captured both perceived and actual visual diversity.

6. Our results suggest that people can perceive variations in biodiversity levels. Our identified visual and acoustic forest characteristics may help to better understand perceived diversity and how it differs from how diversity is measured in biological studies. We present one visual and several acoustic diversity indices that quantify aspects of perceived and actual diversity. These indices may serve as cost-efficient tools to manage and plan greenspaces to promote biodiversity and mental well-being.

KEYWORDS
bird richness, diversity indices, Dr.FOREST, forest biodiversity, forests, perception, senses, sorting task

1 | INTRODUCTION

Amidst a global biodiversity crisis, a growing body of research identifies the importance of biodiversity for people, on both a global level, for example, with regard to ecosystem service provisioning, and the individual level, relating to one's health and well-being (e.g. Marselle et al., 2019, 2021). We are, however, not only experiencing an extinction of species but also an extinction of biodiversity experience due to rural–urban migration and less nature contact (Soga & Gaston, 2016). Here, we need a better understanding of how people experience biodiversity. Which aspects of biodiversity do people predominantly perceive? This understanding may provide leverage points to foster people's interaction with biodiversity and could then help inform natural management strategies that benefit humans and biodiversity conservation (e.g. Pritchard, 2021; Reinecke & Blum, 2018).

There is a consensus across studies that green spaces can provide health-promoting effects (Bowler et al., 2010). For example, visits to the forest directly increase mental health and well-being (Rozario et al., 2024), while indirectly fostering physical health since forests can buffer heat stress (Gillerot et al., 2022, 2024) or improve air quality (Smith et al., 2013; Steinparzer et al., 2022). However, the potential incremental value of biodiversity of such green spaces to health is less understood. A growing research area is working to more finely establish the causal links between biodiversity and mental health and well-being (hereafter, mental well-being; Hedin et al., 2022; Lovell et al., 2014).

Findings, however, are mixed due to variations in study designs and how biodiversity and mental well-being are measured (e.g. Marselle et al., 2019). Biodiversity has different facets as it encompasses variations on the genetic, organismic and ecological level (Heywood & Watson, 1995), which can be described on multiple spatial and temporal scales, and can be further categorised into compositional, functional and structural diversity (Noss, 1990). Thus, there is no single measure of biodiversity and each measure is only a proxy for the 'true' biodiversity it is supposed to describe. The same logic applies for forest diversity, that is, the variety of lifeforms at the genetic or organismic level within a forest ecosystem, including its diversity with regard to ecological functions and habitats. Biologists and forest managers alike therefore rely on a number of measurements—and indices derived from those measurements—to aid them in quantifying forest diversity. The most common measures are structural and organismic diversity. Structural diversity can be quantified by a variety of measures such as diameter at breast height, tree height, basal area (density), canopy layers or leaf area (e.g. Maes et al., 2011; Storch et al., 2018; Van Loy et al., 2003). Organismic diversity, on the other hand, can be quantified not only by tree and understorey plant species richness, but also by the diversity of animal species that rely on the forest habitat for one or more stages of their life cycles, such as forest bird or invertebrate richness. In addition, ecological diversity indices derived from structural or organismic diversity, such as Shannon diversity, are employed to represent a forest's biodiversity. Indices can also measure attributes of a habitat, such as remotely sensed structural indices derived from Light Detection and Ranging (LiDAR) measurements (e.g. the Stand Structural Complexity Index) (Ehbrecht et al., 2017; Frey et al., 2019), and there are also acoustic diversity indices that quantify variations within a soundscape (Towsey 2017). The complexity of sound emanating from a forest habitat can, for example, be assessed with the Acoustic Complexity Index (ACI; Pieretti et al., 2011).

To date, studies investigating the effect of forest diversity on mental well-being have been limited in the number of measures used to represent biodiversity and often select a single (and differing) measure for each study (Grilli & Sacchelli, 2020; Hedin et al., 2022; Marselle et al., 2019). With even a single measure such as species richness, mental well-being responses can further vary depending on species traits and the mental well-being dimension assessed (An et al., 2019; Elsadek et al., 2019; Fisher et al., 2023; Guan et al., 2017; Sivarajah et al., 2018).

Studies also differ in how biodiversity is conceptualised: measured or perceived (Marselle et al., 2021). Perceived biodiversity refers to subjective estimations of the biodiversity present in an environment (Dallimer et al., 2012; Fuller et al., 2007; Rozario et al., 2024). Most studies demonstrate a relationship between perceived and measured diversity (Ferraro et al., 2020; Fuller et al., 2007; Gao et al., 2019; Gonçalves et al., 2021; Johansson et al., 2014; Lindemann-Matthies et al., 2010; Rozario et al., 2024; Southon et al., 2018) but associations are often weak (Rozario et al., 2024) or non-existent (Dallimer et al., 2012; Phillips & Lindquist, 2021; Stobbe et al., 2022). This indicates that, despite a substantial overlap, there is a divergence between biodiversity measured by biologists and how people perceive it.

Studies have also juxtaposed the associations of measured and perceived biodiversity with mental well-being. In these cases, perceived biodiversity was found to have a stronger effect on mental well-being than measured biodiversity (Cameron et al., 2020; Dallimer et al., 2012; Farris et al., 2024; Rozario et al., 2024; Schebella et al., 2019; Zumhof, 2019). Indeed, Rozario et al. (2024), Farris et al. (2024) and Zumhof (2019) only found significant mental well-being effects for perceived biodiversity. A more nuanced differentiation between measured and perceived biodiversity is hence needed to understand their respective effects on mental well-being.

Importantly, perceiving biodiversity is a multisensory experience (Franco et al., 2017; Hedblom et al., 2019). Given the disproportionate amount of studies focused on the visual sense, a better understanding of the contribution of other senses (individually and combined) to perceiving biodiversity—and its effects on mental well-being—is desirable. Fisher et al. (2023), for instance, found that sounds were among the most frequently recognised forest diversity characteristics, alongside visual cues such as colour, and that sounds elicited the greatest well-being responses. Higher levels of acoustic diversity, in terms of vocalising bird species, have further been shown to reduce symptoms of depression (Stobbe et al., 2022), increase feelings of awe (Romero et al., 2025) and elicit more pronounced restorative effects (Ferraro et al., 2020; Uebel et al., 2021). The acoustic sense in particular may thus be crucial to obtain a more thorough understanding of perceived biodiversity.

For the visual sense, several studies investigated potential drivers of perceived diversity (Gonçalves et al., 2021; Hoyle, 2020; Hoyle et al., 2018; Southon et al., 2018). Hoyle et al. (2018) identified flower colour as a significant predictor of perceived plant richness, that is, colourful meadows were perceived as more biodiverse. Southon et al. (2018) report higher perceived diversity ratings for meadows that were perceived as more colourful but also for meadows with greater vegetation height and evenness. Tree evenness and fruit showiness, however, were negatively associated with perceived diversity in urban parks, while positive links were found with species richness, butterfly evenness, leaf shape and evergreen species (Gonçalves et al., 2021). Conversely, no study to date has investigated potential drivers of perceived acoustic diversity.

Human perception combines realism with constructivism, as it involves both bottom-up processing of objectively measurable sensory information (realism) that is nuanced by top-down processing (constructivism) through involving higher level mental functions, such as memory of past experiences, cognition (e.g. knowledge, expectations, attention and motivation) and emotions (Axelrod, 1973; Brunswik, 1952; Friston, 2005; Gregory, 1980; Koffka, 1922). It is these top-down processes that determine what is ultimately perceived (e.g Axelrod, 1973). A more holistic understanding of perceived biodiversity therefore requires integrating different sources of knowledge, as it is the consequence of how objectively measurable biophysical properties such as colour for the visual sense or sound pressure level for the acoustic sense are translated into sensory input and how this sensory input is further processed and interpreted by the mental system.

With a focus on the visual and acoustic senses, we therefore aim to identify biophysical and subjective factors that influence perceived biodiversity. We further investigate how laypeople's perception of visual and acoustic diversity relates to proxies of actual forest diversity (based on species richness and expert ratings of structural diversity) and established ecological diversity indices. Our specific research questions are:

1. What do people perceive when seeing or hearing different levels of biodiversity?
2. How congruent are actual and perceived diversity?
3. Are there diversity indices to quantify both perceived and actual diversity?

We test this using photographs and audio recordings of forest environments. In essence, limited to two senses, we assess what people experience in a forest, and if we can measure it. Based on this understanding, if we can identify diversity indices that simultaneously quantify actual forest diversity, based on species richness and expert ratings of structural diversity and people's perceptions of it, we can use these indices towards managing natural spaces both to increase biodiversity and their experienced value that could foster mental well-being.

2 | METHODS

We conducted sorting experiments (Chollet et al., 2014; Lobinger & Brantner, 2020) to make mental representations associated with forest diversity tangible (Austen et al., 2021, 2023). Participants sorted forest photos ('visual sort') and audio recordings ('acoustic sort') of varying forest biodiversity, to identify subjective visual and acoustic forest characteristics that stood out to them and to obtain perceived visual and acoustic diversity ratings (Figure 1, Step 1). These ratings were then correlated with proxies of actual biodiversity for the stimuli (further referred to as actual diversity) (Figure 1, Step 2). Next, we computed diversity indices from the photographs and recordings

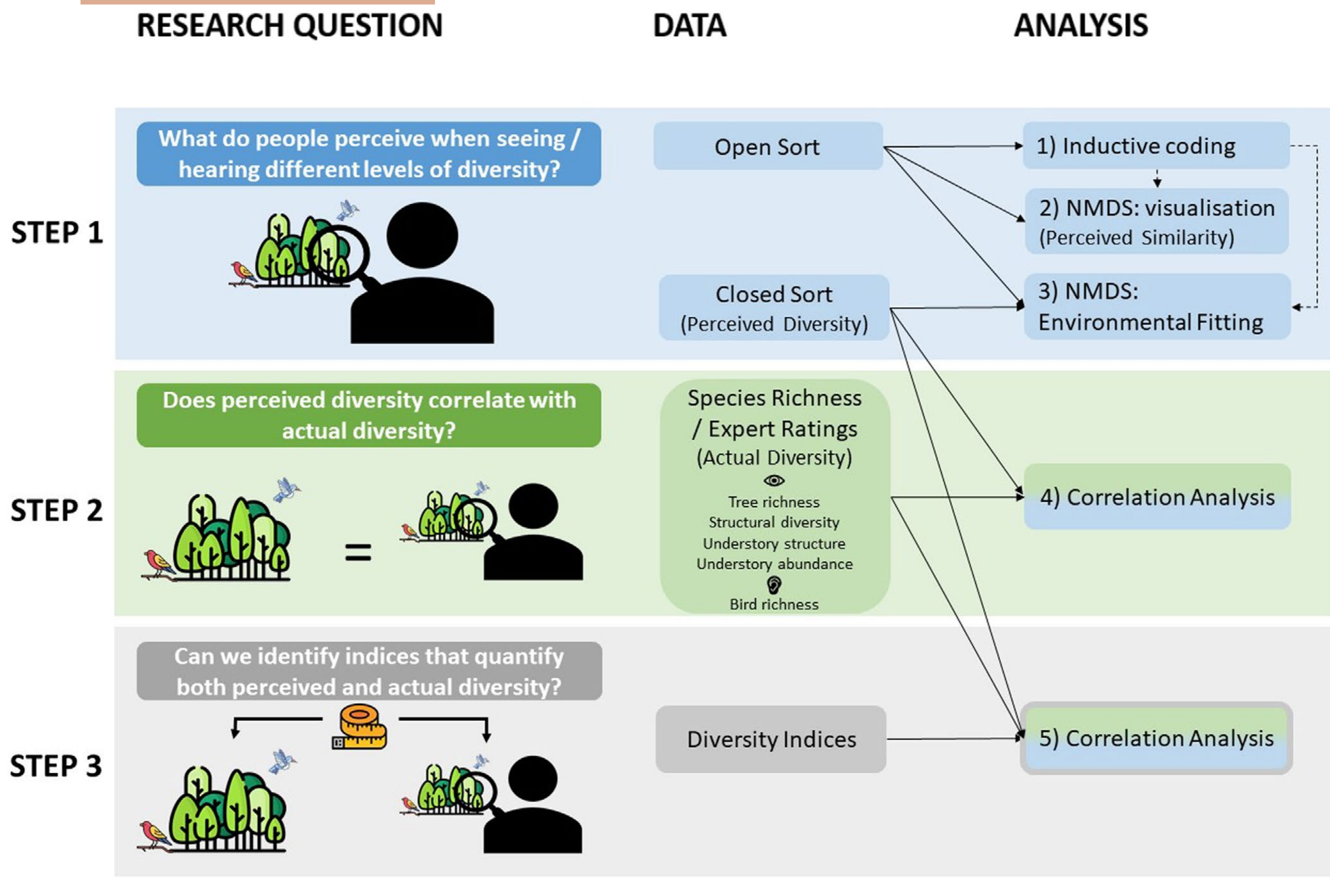

FIGURE 1 Conceptual figure of the study objectives. NMDS, non-metric multidimensional scaling. Solid arrows indicate that data were used for respective analyses. Dashed arrows show the conceptual relationship between the sorting criteria and the NMDS plots/environmental fitting.

and tested if these indices were correlated with actual and perceived diversity (Figure 1, Step 3).

2.1 | Stimulus materials and actual diversity

The stimulus set for the visual sort comprised 57 pre-selected forest photographs depicting varying levels of forest biodiversity (see Appendix S1 for detailed information about the photographs and Figure 2 and Figure S1 for examples). Photographs were taken in temperate forests managed with close-to-nature forestry schemes in Germany (Hainich), Belgium (TREEWEB forest patches, https://treedivbelgium.ugent.be/pl_treeweb.html) and Poland (Białowieża) in late summer 2020 under consistent weather and time conditions (cloudy to sunny/11:00 AM—4:00 PM; see Bergen et al., 1995; Carrus et al., 2015; Hofmann et al., 2017), with an iPhone 6s (12-megapixel camera) and a polarisation filter in order to parcel out scattered light that reduces image quality. We further took the photos at a height of ~1.80 m to ensure a realistic human observer perspective (Grassini et al., 2019). Forest patches were pre-identified and categorised based on tree species richness by forest ecologists and local forestry agencies. To derive the most accurate proxy of actual forest diversity based on the photographs, we assessed four commonly used forest diversity indicators that we combined into a single metric for actual diversity: tree species richness, forest structural diversity, understorey structural diversity and understorey abundance (e.g. Maes et al., 2011; Van Loy et al., 2003). The tree species richness for each photo was based on the conducted forest inventories and verified by the photographer (KR) who was trained to identify regional tree species. Tree species richness therefore constitutes count data. An expert-based survey was further conducted to obtain data for the other three indicators (see e.g. Carrus et al., 2015): two forest ecologists (BJ and MSL) rated the 57 photos according to low, medium or high forest structural diversity, understorey structural diversity and understorey abundance. The final values for actual visual diversity for each photo were then obtained by computing the mean of the sum of z-standardised tree species richness, forest structure, understorey structure and understorey abundance scores. Photos were printed out in A5 format and laminated for multiple use.

The stimulus set of the acoustic sort consisted of 16 ten-second-long (Ratcliffe et al., 2016, 2020) natural audio recordings taken from the same temperate forest patches as the photographs (see Appendix S2 for detailed information about the audio recordings and Table S2 for examples). Actual acoustic diversity in these recordings was operationalised via vocalisations from varying numbers of unique bird species (bird species richness), from zero to six

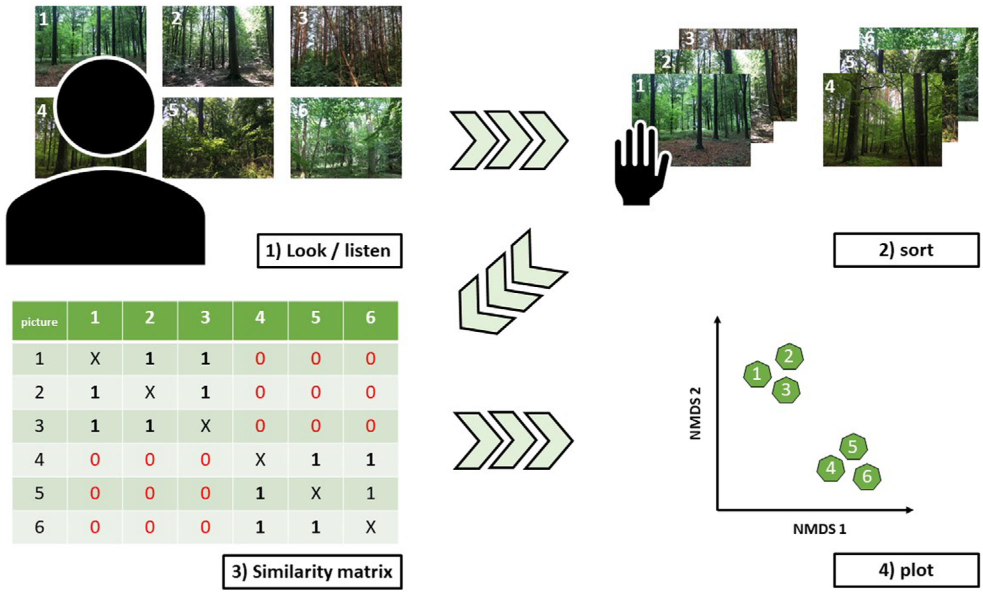

FIGURE 2 Schematic overview of the non-metric multidimensional scaling (NMDS) procedure using the open visual sort as an example. Each cell of the similarity matrices contained count values of common assignments of pairs of photos/recordings to categories. In this example, photos 1, 2 and 3 have been assigned to the same category, so a '1', representing one count, appears at the intersection of respective photos in the similarity matrix.

bird species in a given recording. We used fewer stimuli in acoustic sorts than in the visual sort because recordings had to be listened to sequentially. It would have thus been overly cognitively demanding and time-consuming for participants to remember (and re-play) 57 sound clips in order to complete the task (see e.g. Berland et al., 2015; Giordano et al., 2011; Maffiolo et al., 1998 for numbers of audio recordings in other acoustic sorts).

2.2 | Participants

For the visual sort, we tested 48 participants (41 women, 85%) between 18 and 35 years of age (M = 23.92, SD = 4.20). While reasonable sorting clusters can be obtained with 20–30 participants (Chollet et al., 2014; Harloff & Coxon, 2007; Rugg & McGeorge, 2005; Tullis et al., 2004), we chose to work with a higher number of participants, as the robustness of results in sorting studies increases with the number of participants (Berland et al., 2015; Blancher et al., 2012). Robustness further increases as a function of participants' expertise with the stimuli to be sorted and decreases with higher task complexity (Blancher et al., 2012). A majority of the study participants were psychology students, thus with little expertise in ecology or forestry. In addition, we assumed that the complexity of the visual sort was considerably high as (i) the content of the photographs was similar which impedes the clustering of photos in the sorting process and (ii) the number of photos exceeded recommendations (see Chollet et al., 2014; Rugg & McGeorge, 2005) which poses an increased demand on working memory capacity. For the acoustic sort, we also tested 48 participants (34 women, 71%) between 18 and 35 years of age (M = 24.33, SD = 4.45) to achieve an equivalent sample size.

Prerequisites for study participation were good general health as well as normal or corrected-to-normal vision (visual sort) and hearing (acoustic sort). Participants for both studies were recruited through the mailing list of the Cognitive and Biological Psychology group of the Wilhelm Wundt Institute for Psychology at Leipzig University, various social media platforms and word of mouth. The procedure for both studies followed the principles of the Declaration of Helsinki. Ethical approvals were obtained from the local ethics committee at Leipzig University (reference number visual sort: 2021.02.26_eb_77; reference number acoustic sort: 2022.07.07_eb_163). All participants gave written informed consent prior to participation. There was no financial remuneration; psychology students (visual sort: $n = 24$; acoustic sort: $n = 27$) received course credits that equalled the time spent at the experiment in hours.

2.3 | Procedure

Data collection took place from March to May 2021 (visual sort) and August to November 2022 (acoustic sort) in facilities of Leipzig University and the German Centre of Integrative Biodiversity Research (iDiv).

For both the visual and acoustic sort, we combined two single-criterion open sorts with one closed sort (see Canter, 1996; Chollet et al., 2014; Harloff & Coxon, 2007; Rugg & McGeorge, 2005 for different sorting paradigms). In open sorts, participants were free to sort objects according to any similarity-based sorting criterion they liked. For example, a participant could choose to sort the forest photos based on sorting criteria, such as vegetation density or colour. They then chose subordinate categories to assign the photos to, for example, along a gradient such as low, medium and high vegetation density. In closed sorts, participants are asked to sort objects based on pre-established criteria. In the closed visual sort, we asked participants to sort the photographs according to low, medium and high forest biodiversity (Phillips & Lindquist, 2021; White et al., 2017). We provided a short definition of biodiversity according to the Convention on Biological Diversity (1992), that is, biodiversity as the diversity of species, genetic variations within species and diverse ecosystems in our instructions to participants. In the closed acoustic sort, we asked participants to sort the audio recordings according to low, medium and high acoustic diversity. No definition of acoustic diversity was provided (see Appendix S3 for written instructions of the visual and acoustic sorts).

For the visual sorts, participants were instructed to distribute the 57 photos on either the floor or tables in a way that enabled parallel viewing of all photos. Sound recordings for the acoustic sorts were digitally presented on the desktop of a Dell Latitude E7440. Participants listened to the recordings with headphones (HyperX Cloud Stinger™ Core) and loudness was set to volume level 34 locally on the laptop. We instructed the participants to listen to all 16 sound recordings at least once but as often as they liked before and while sorting.

In both experiments, participants began with the two open sorts as conducting the closed sort prior to the open sorts would have potentially primed the sorting behaviour in the open sort towards diversity. We conducted two open sorts to obtain more visual and acoustic forest characteristics from the participants and to increase the robustness of the results (Blancher et al., 2012). The instructions for the open sorts were identical for the open visual and acoustic sorts and for the two open sorts conducted per sense, with the restriction that two distinct sorting criteria had to be employed (e.g. 'vegetation density' for the first open visual sort and 'colour' for the second open visual sort; see Appendix S3). For each open sort, participants had to identify at least two subordinate categories (e.g. low and high vegetation density). At least one sorting object had to be assigned to each sub-category.

Sorting criteria and sub-categories, as well as the assignment of photos and audio recordings to sub-categories, were recorded on documentation sheets. Numbers on the back of each photograph, as well as labels for the audio files on the desktop, were used to track the assignment of stimuli to sub-categories. Results were captured in paper–pencil format. The time of data collection varied between 1.5 and 3.5 h for the visual sorts and between 1 and 1.5 h for the acoustic sorts since no time restriction was given.

2.4 | Diversity indices

We wanted to test if we could compute diversity indices from the stimuli (photos/recordings) that measured actual and perceived diversity (see Figure 1, Step 3). Four visual indices were selected to reflect diversity related to characteristics of photographs that participants might observe, such as the intensity of green, colour as proxy for vegetation biomass and variations in light (Frey et al., 2019; Hasler & Süsstrunk, 2003; Menzel & Reese, 2021). We also computed four acoustic indices known in prior studies as reliable indicators of biodiversity (Alcocer et al., 2022; Yip et al., 2021). These indices quantify different characteristics of an acoustic recording, for example, the complexity of a bird vocalisation, density of calls within a recording or the frequency bands that birds vocalise in (e.g. low-frequency pigeon 'coos' vs higher frequency warbles). Indices were selected to also match an accompanying study where respective indices were related to forest features (Gillerot et al., 2025). See Table 1 for a list of the computed indices, Appendix S4 for summary statistics and code used to compute them and Appendix S5 for correlations between indices.

2.5 | Statistical analyses

2.5.1 | Perceived visual and acoustic forest characteristics

We qualitatively analysed the sorting criteria reported by participants in the open sorts, to better understand the perceived forest characteristics that potentially influenced perceived diversity (Figure 1 Step 1, Analysis 1). In total, 92 open visual sorts and 96 open acoustic sorts were completed and analysed separately. Overarching clusters within the sorting criteria were identified following a general inductive approach, that is, clusters were formed in a bottom-up manner based on the precise wording of the sorting criteria given by participants (Thomas, 2006). To increase objectivity, we conducted independent parallel coding (Thomas, 2006) with five raters from various disciplines (KR (psychology), MM (psychology), RRYO (ecology), MGB (philosophy) and OS, listed in the acknowledgements (neurosciences)), the results of which we refer to as first-order clusters. Raters could form as many first-order clusters as they considered appropriate to cover the variety of themes they identified in the sorting criteria. At least one first-order cluster had to be assigned to each sorting criterion. First-order clusters were then further summarised by one rater (KR) to form the final set of eight perceptual visual and acoustic forest characteristics (Thomas, 2006), hereafter referred to as second-order clusters.

2.5.2 | Perceived visual and acoustic forest similarity

All the following analyses were computed in R Statistical Computing Environment (version 4.2.1; R Core Team, 2022). We applied non-metric multidimensional scaling (NMDS) on the open sort data to assess how similar the photographs and recordings were perceived in relation to one another (Figure 1, Step 1, Analysis 2). Similarity or co-occurrence matrices of the sizes 57 × 57 (open visual sort) and 16 × 16 (open acoustic sort) were calculated by comparing pairs of photos or recordings for each participant. For each pair, we counted the number of common assignments to sub-categories. These counts were then

TABLE 1 Computed indices on visual and acoustic stimuli.

Index	Description	Presumed link with biodiversity	Citation
Greenness	A quantification of the green values comprising a digital RGB photograph as one aspect of the Red-Green-Blue Vegetation Index. Higher values indicate more greenness	Photosynthetic activity, that is, biomass/greater primary productivity	Bendig et al. (2015), Frey et al. (2019) and Lussem et al. (2018)
Brightness	Converts image to greyscale, and quantifies how close to white the average pixel value is. Higher values indicate more brightness	Forest/vegetation density probably lower in photos with greater brightness, as greater brightness could indicate more light/less vegetation	Frey et al. (2019), Ibarra et al. (2017), Kardan et al. (2015) and Menzel and Reese (2021)
Brightness SD (standard deviation)	As a measure of light contrasts, this index takes the mean of the brightness index above and quantifies the amount of variation in light versus dark values present in the photograph. Higher values indicate stronger contrast	Dappling effects on the forest floor resulting in alterations of light, heat/temperature and moisture, which in turn affect growth and survival of the ground vegetation; uniform brightness may indicate homogeneous forest structures, while a great variability of the brightness may indicate a diverse habitat structure	Frey et al. (2019), Ibarra et al. (2017), Kardan et al. (2015) and Menzel and Reese (2021)
Colourfulness	A quantification of colourfulness calibrated on the perception of participants based on the standard deviations and mean values within an opposing colour space defined along the red-green axis against the blue axis. Higher values indicate more colours	More colourful photos may indicate a greater and more diverse range of tree and plant species	Hasler and Süsstrunk (2003)
Acoustic Complexity Index (ACI)	Designed to reflect complex sound, the ACI captures rapid variations in frequency and amplitude that are typical of biophony, that is, biotic components of a soundscape (especially birdsong). This index typically does not respond to persistent sound such as machinery noise or buzzing insects. Higher values indicate greater biophony	Greater biophony as an indicator of greater vocalising animal species richness and/or abundance	Pieretti et al. (2011) and Towsey (2017)
Events per second	Quantifies variations of quiet-to-loud events. The number of acoustic events per second in each noise-reduced frequency bin, where an event is counted each time the decibel value in a bin crosses the 3 dB threshold from lower to higher values, then divided by the number of seconds in the audio file. Higher values indicate more events per second in the audio recording	More acoustic events in the recording could indicate greater abundance of vocalising animals or an animal with a more complex vocalisation	Towsey (2017)
Activity	The fraction of values in the noise-reduced decibel envelope that exceed the threshold of 3 dB. Generally increases with more events in sound files. Higher values indicate more events in the audio recording	More acoustic events in the recording could indicate greater abundance of vocalising animals or an animal with a more complex vocalisation	Towsey (2017)
Mid frequency cover	The fraction of noise-reduced spectrogram cells that exceed 3 dB in the mid-frequency band (1000–8000 Hz), where biophony is typically present, including birdsong. Higher values indicate more biophonic events in the audio recording	Greater biophony as an indicator of greater vocalising animal species richness and/or abundance	Towsey (2017)

used to populate the corresponding cells in the matrices (see Figure 2 for a schematic overview of the procedure). We then calculated Canberra distances (Gerstenberg & Hofmann, 2016) to convert the similarity matrices into dissimilarity matrices as Canberra distances are well suited for non-standardised count data and particularly robust to outliers (Roberts, 2017). Afterwards, we computed an NMDS analysis using the *vegan* package (Oksanen et al., 2007). We selected the number of appropriate NMDS dimensions based on stress values (below 0.1; Kruskal, 1964). Two NMDS dimensions produced stress values of 0.06 for the visual sort and 0.04 for the acoustic sort indicating fair-to-good fit of the data to reduced ordination space.

2.5.3 | Perceived visual and acoustic forest diversity

Perceived diversity ratings for the visual and acoustic stimuli were calculated using data from the closed sorts. The three levels of the closed sorts were coded as low diversity = 1, medium diversity = 2 and high diversity = 3. Mean perceived diversity scores were calculated for each photo and recording, respectively. To validate whether we could describe perceived diversity well with the open sort criteria, we conducted an environmental fitting analysis (Figure 1, Step 1, Analysis 3). This enabled us to investigate whether perceived diversity explained the participants' open sorting patterns, that is, the produced NMDS solutions, using the 'envfit' function in the *vegan* package (Oksanen et al., 2007).

2.5.4 | Associations between perceived and actual diversity and diversity indices

Finally, we tested the correlation between perceived and actual diversity (Figure 1, Step 2), and between the diversity indices with both perceived and actual diversity (Figure 1, Step 3). Pearson's correlations were used for parametric data, and Spearman's correlations were used for non-parametric data, both using the *stats* package (R Core Team, 2022).

3 | RESULTS

3.1 | Perceived diversity

3.1.1 | Perceived forest characteristics

The five raters assigned 501 first-order clusters to the original sorting criteria of the open visual sort (see Appendix S6 for the five raters' first-order clusters). Based on those first-order clusters, eight second-order clusters were identified comprising vegetation density, light conditions, structure, colour, diversity, emotions, the ground layer and tree physical features, in descending order.

For the acoustic sort, a total of 507 first-order clusters were assigned to the sorting criteria (Appendix S6). The eight second-order clusters identified were as follows: bird song characteristics, physical properties of the sound recordings, time, emotions, bird abundance, bird species, vitality of vocalisations and landscape features in descending order. Tables 2 and 3 show descriptions, examples and frequencies of the second-order clusters for the visual domain and acoustic domain, respectively.

3.1.2 | Perceived similarity

Environmental fitting indicated that perceived visual similarity, that is, the sorting pattern in the open visual sorts, was significantly associated with perceived visual diversity in the closed sort ($p < 0.001$, $R^2 = 0.58$; Figure 1, Step 1, Analysis 3). Perceived acoustic similarity was also significantly associated with perceived acoustic diversity ($p < 0.001$, $R^2 = 0.96$), indicating that the open sorts (and the in 3.1.1 identified forest characteristics) represent aspects of perceived visual and acoustic diversity well (Figure 3, see Appendix S7 for the

TABLE 2 Visual forest characteristics identified in the open sorts.

Forest characteristics	Description	Examples	Frequency
(1) Vegetation density	The density of all kinds of vegetation	Leaf density, vegetation density, tree density, forest density	86 (20.82%)
(2) Light conditions	The light/brightness in the photographs, for example, through mentioning sun rays or shadows	Light and shadow, solar radiation, light on the forest floor, light flooding, brightness	80 (19.37%)
(3) Structure	Forest structural attributes, for example, vertical/horizontal forest structure but also the level of disturbance/management	Order and regularity, arrangement of trees, structure/level of organisation, cultivation, naturalness/disturbance	64 (15.50%)
(4) Colour	With references to colour	Trunk colour, leave colour, warmth/colour, forest/tree colour depending on solar radiation	54 (13.08%)
(5) Diversity	The diversity of living organisms	Species, diversity, dominant tree species, biodiversity	45 (10.90%)
(6) Emotions	Emotions or the atmosphere in the photographs	Mood, mystic, inviting atmosphere, cosiness, level of well-being	33 (7.99%)
(7) Ground layer	The forest floor mostly with references to the herbal layer/ground vegetation but also the accessibility of the forest	Coverage of the moss and soil layer, light on the forest floor, condition of the forest floor/coverage, forest floor vegetation, accessibility	27 (6.54%)
(8) Tree physical feature	Biophysical features of trees, in particular the trunk	Trunk colour, forms and size, perspective/height, width of trunks, thickness of trunks	24 (5.81%)
			$n = 413$[a]

Note: A summary of the eight forest characteristics (second-order clusters) identified in the open visual sort, sorted by frequency (the most frequent cluster is in the first row) and accompanied by a description and examples. Second-order clusters are the result of qualitatively clustering the first-order clusters which were assigned to the original sorting criteria by five independent raters. Taken together, 501 first-order clusters were assigned to the criteria by all raters.

[a]88 first-order clusters were not covered by the second-order clusters due to their specificity.

TABLE 3 Acoustic forest characteristics identified in the open sorts.

Forest characteristics	Description	Examples	Frequency
(1) Bird song characteristics	With references to bird song characteristics	Melodic diversity of bird songs, complexity of bird melodies, rhythm (repetitiveness/pattern), dominance of bird songs, bird's chirping	95 (20.89%)
(2) Physical characteristics	Physical characteristics of the recording as well as the perceived distance of sounds	Volume, noise intensity, bird song intensity, amount of tones, distance to sounds, salience and frequency, speed	74 (16.26%)
(3) Time	The time of day or the season when the sound was recorded	Time of day, imagined time of day, seasons, place and time	73 (16.04%)
(4) Emotions	Emotions or the atmosphere in the recordings	Emotional feeling, mood, feeling of relaxation and idyll (quietness), valence	72 (15.82%)
(5) Bird abundance	The number of birds that are noticeable	Amount of birds, biodiversity/abundance, mood/amount of paramount voices, amount of bird chirping	47 (10.33%)
(6) Bird species	Bird species and bird species richness	Amount of birds and bird species richness, biodiversity/abundance, chirping types, amount of different bird songs (species), different birds	33 (7.25%)
(7) Vitality	The vitality and sensations of the birds	Bird's state of alarm, liveliness, signal effect/emotion, birds' mood	32 (7.03%)
(8) Landscape	Landscape features	River, place/landscape, forest density, landscape	29 (6.37%)
			$n=455$[a]

Note: A summary of the eight forest characteristics (second-order clusters) identified in the open acoustic sort, sorted by frequency (the most frequent cluster is in the first row) and accompanied by a description and examples. Second-order clusters are the result of qualitatively clustering the first-order clusters which were assigned to the original sorting criteria by five independent raters. Taken together, 507 first-order clusters were assigned to the criteria by all raters.

[a]52 first-order clusters were not covered by the second-order clusters due to their specificity.

results of environmental fitting with perceived diversity, actual diversity and the diversity indices).

3.2 | Relationship between perceived and actual diversity

Positive significant correlations were found between perceived and actual diversity (Figure 1, Step 2) for both the visual and acoustic stimuli (visual: $Rho=0.76$, $p<0.001$; acoustic: $Rho=0.87$, $p<0.001$; Figure 4; see Appendix S8 for results of correlation analysis of tree species richness/structural diversity/understorey structural diversity and understorey abundance separately with perceived visual diversity).

3.3 | Relationships between the computed diversity indices and perceived and actual diversity

Associations between the computed diversity indices and perceived diversity were mixed (Figure 1, Step 3; Table 4). Only one computed visual diversity index (Greenness) was significantly positively correlated with perceived visual diversity (Figure 5a–d). All four computed acoustic indices, however, were significantly positively correlated with perceived acoustic diversity (Figure 5e–h).

Finally, when comparing the computed diversity indices with actual diversity (Figure 1, Step 3), results followed a similar pattern to the comparison with perceived diversity (Table 4). While the Greenness Index was also positively related to actual visual diversity, there was a negative association between the Brightness Index and actual visual diversity (Figure 6a–d). This indicates that higher proportions of green pixels and lower deviations of grayscale values from white in a photo are associated with greater actual visual diversity (see Appendix S8 for results of correlation analysis of tree species richness/structural diversity/understorey structural diversity and understorey abundance separately with the visual indices). All four acoustic indices were significantly positively correlated with actual acoustic diversity, that is, bird species richness (Figure 6e–h).

4 | DISCUSSION

We could show in our study, focusing on the visual and acoustic sense, that perceived and measured forest biodiversity are significantly correlated—both for actual diversity and, to a lesser extent, the computed diversity indices. We identified perceived forest characteristics that

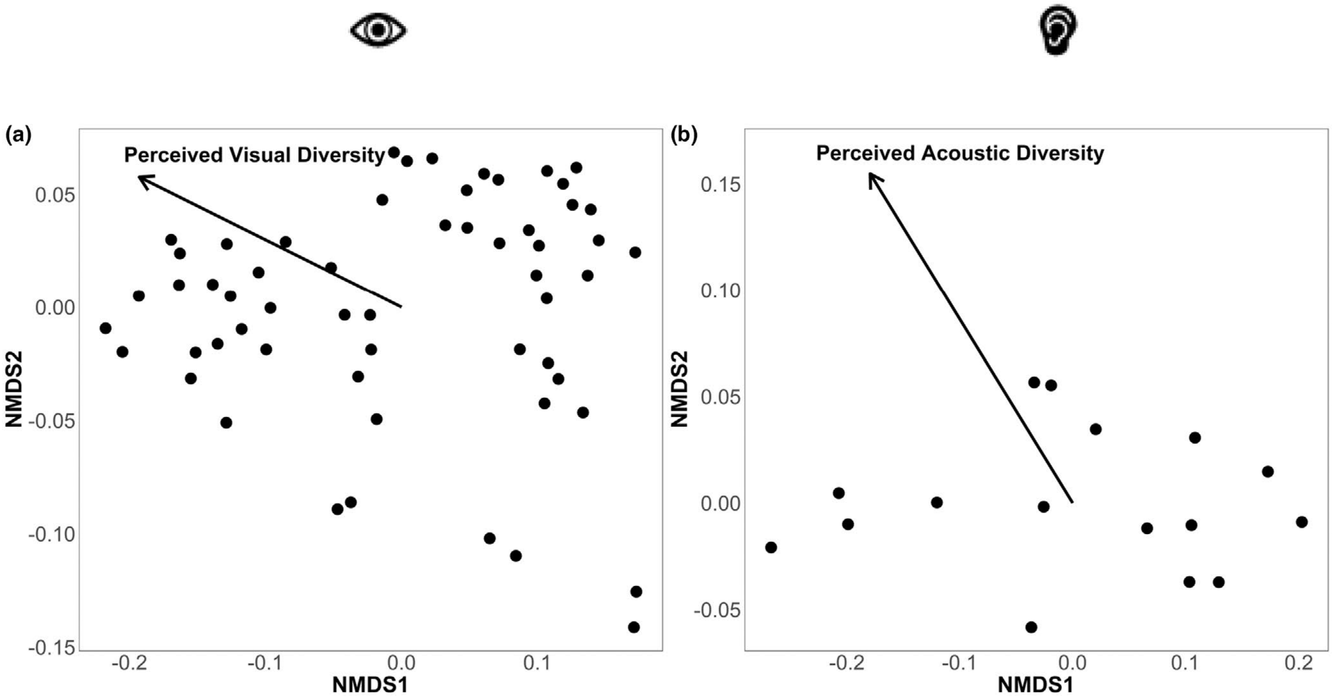

FIGURE 3 Non-metric multidimensional scaling (NMDS) plots resulting from the open visual (a) and open acoustic sort (b) (stress values: visual: 0.06; acoustic: 0.04). Points represent photos and recordings, respectively. The closer two points (shorter distance), the more similar photos or recordings were perceived to be. Environmental fitting was conducted to see whether perceived diversity aligns with the produced NMDS solutions. The arrows illustrate the direction and strength of the associations between perceived diversity and the NMDS solutions.

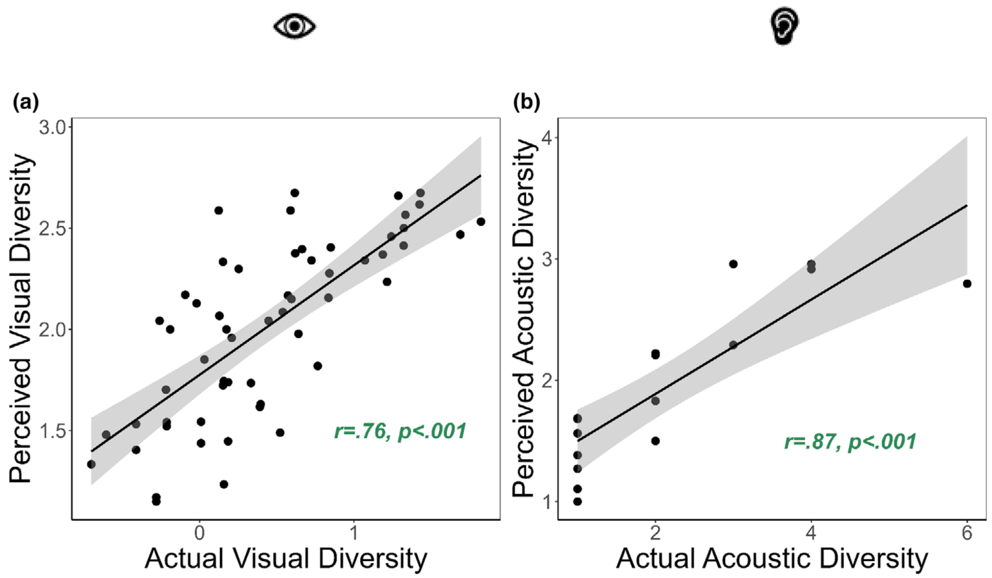

FIGURE 4 Correlation between actual diversity and mean perceived visual (a) and mean perceived acoustic (b) diversity per stimuli (57 photos and 16 audio recordings). Perceived diversity was rated by participants. Lines represent linear regressions and shaded areas represent a 0.95 confidence interval.

could help bridge the gap between perceived and actual diversity: For the visual sense, these were mainly structural parameters, for example, vegetation density, light conditions, colours and forest structure. For the acoustic sense bird song characteristics, perceived physical properties such as volume, time of day as well as seasonal alterations and evoked emotions were the most frequently identified cues.

4.1 | Perceived forest characteristics

Perception involves more than just the objectively measurable biophysical aspects. It also includes top-down processes like prior experiences, memories, knowledge, emotions, and individual physiological features that influence how we ultimately perceive things (e.g. Axelrod, 1973). We therefore identified subjective visual and acoustic forest characteristics in the open sorts to complement our understanding of what aspects perceived diversity may consist of. The identified characteristics reflect both the bottom-up processing (e.g. colours of the forest, physical characteristics of the recordings) and top-down processing (e.g. emotions, time of day). The significant environmental fitting analysis showed that the open sorts correlated with perceived visual and acoustic diversity (Figure 1, Step 1), making the identified visual and acoustic forest characteristics likely candidates to better understand perceived visual and acoustic diversity.

For the visual sense, several of the perceived forest characteristics we identified aligned with work from Austen et al. (2021, 2023), where shared perspectives on forest diversity attributes were identified by asking people to sort illustration cards of four different taxa in different seasons. In our study, the most commonly used sorting criteria were vegetation density and light conditions, while in the Austen et al. (2021, 2023) studies, these themes have been identified as meaningful concepts in sorts targeting trees in autumn only. Austen et al. (2021, 2023), however, presented single or few species on their illustration cards and no whole forest ecosystem as in the photographs of our study. As such, the participants' attention in the Austen et al. (2021, 2023) studies may have been focused on characteristics of the depicted trees alone—rather than visual cues resulting from the interplay of several trees such as forest density or variations of light. As in our study, previous work also found that colour matters for perceived visual diversity (Austen et al., 2021, 2023; Hoyle et al., 2018). We further found that emotions and memories influenced the sorting strategies of participants which has also been reported by Austen et al. (2021, 2023) in their sorting experiment.

TABLE 4 Correlation coefficients of comparisons between diversity indices, perceived diversity and actual diversity.

Index	Perceived diversity	Actual diversity
Greenness	**0.39****	**0.42****, ◊
Brightness	−0.21	**−0.33***, ◊
Brightness SD	0.25	0.25
Colourfulness	0.15	0.08◊
Activity	**0.60***, ◊	**0.59***
Events per second	**0.74****, ◊	**0.65****
Mid frequency cover	**0.96*****	**0.81*****
Acoustic complexity	**0.80*****	**0.71****

Note: All tests were Spearman correlation tests, unless denoted by a ◊, indicating a Pearson correlation. Significant correlations are bolded and indicated as follows: <0.05*, <0.01**, <0.001***.

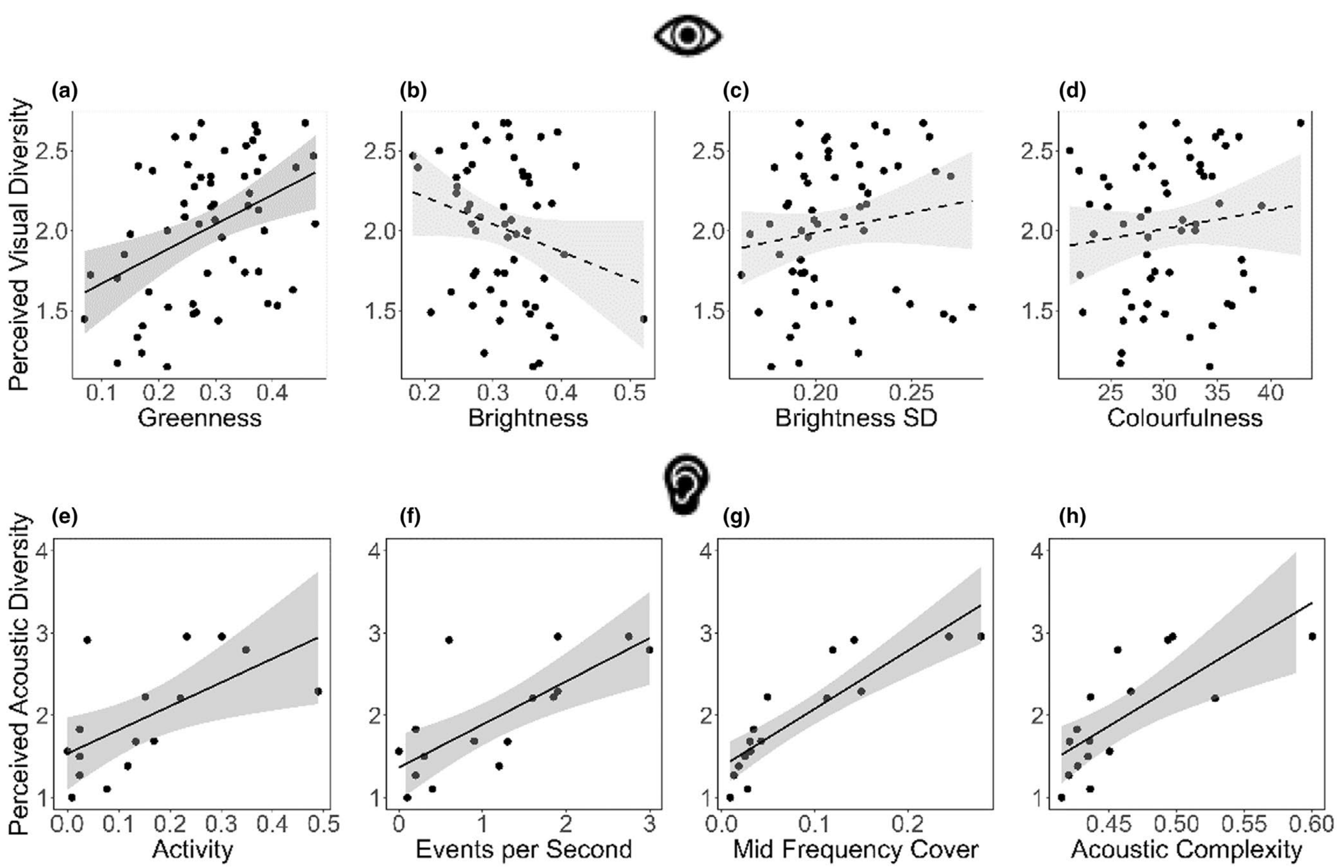

FIGURE 5 Correlations between the computed indices and perceived diversity. Panels (a–d) show correlations for visual indices derived from the photographs, and panels (e–h) represent acoustic indices derived from the audio recordings. Solid lines present significant correlations, and dashed lines represent nonsignificant correlations; see details in Table 4. Shaded areas represent a 0.95 confidence interval.

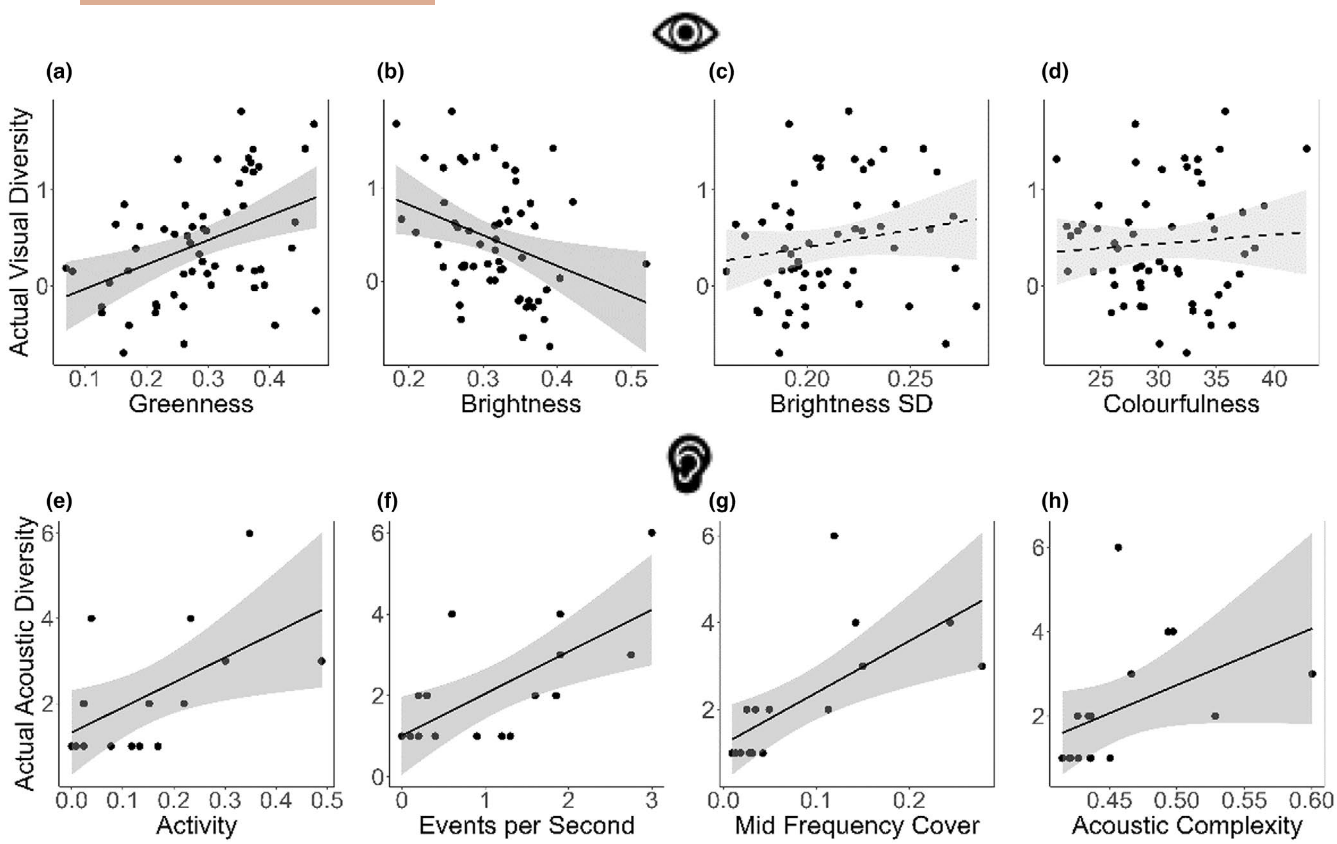

FIGURE 6 Correlations between the computed indices and actual diversity. Panels (a–d) show correlations for visual indices and actual visual diversity, both derived from the photographs. Panels (e–h) show correlations for acoustic indices and actual acoustic diversity, both derived from the audio recordings. Solid lines present significant correlations and dashed lines represent non-significant correlations, see details in Table 4. Shaded areas represent a 0.95 confidence interval.

The perceived acoustic forest characteristics we identified support previous findings from studies that addressed bird sound perception (Ratcliffe, 2021; Ratcliffe et al., 2013, 2016, 2020). Participants in our study most often sorted the recordings according to bird song characteristics such as properties of the chirps, perceived melodic and repetitive patterns or complexity. Studies on the restorative potential of bird sounds have identified similar acoustic properties as those examined here. Both qualitative (Ratcliffe et al., 2013, 2016) and quantitative (Ratcliffe et al., 2020) research highlight factors such as sound volume (Ratcliffe et al., 2013, 2020), associations with time of day or seasonal changes (Ratcliffe et al., 2016), affective responses (Ratcliffe et al., 2013) and connections to landscapes where the sounds were recorded (Ratcliffe et al., 2016). While we did not test the restorative potential of diversity in this study, previous studies have shown that perceived acoustic diversity (Uebel et al., 2021) and visual diversity (Rozario et al., 2024) are associated with restorative and mental well-being outcomes.

With our study, we provide evidence that there are measurable, bottom-up-driven aspects of forests that people intuitively recognise when viewing forest photographs or hearing forest sound recordings, such as vegetation density or features of bird song, while we also identified top-down-driven, subjective mental representations, such as evoked emotions. While top-down cognitive processes are hard to generalise, future research could elaborate on the link between the identified biophysical forest features and how these translate into perceived biodiversity. For example, participants could be asked to sort stimuli wherein, for example, species richness remains unchanged but other aspects, such as vegetation density, brightness and colourfulness for perceived visual diversity, and melodic patterns or volume for perceived acoustic diversity are varied. Moreover, items that allow people to freely rate biodiversity according to their own understanding of biodiversity can be useful in studies where drivers of perceived diversity are tested in addition to their well-being effects. Rozario et al. (2024), for instance, asked participants how biodiverse they thought an environment was on a continuous scale from 0 (no biodiversity) to 100 (extremely biodiverse), and found that higher perceived diversity measured with this item was related to several mental well-being measures. These items can serve as outcome variables to test how factors such as vegetation density (visual perception) or sound volume (auditory perception) influence perceived diversity. Future studies may further compare different psychological theories of perception, such as Schema Theory (Axelrod, 1974) or Gestalt Theory (Koffka, 1922), to better understand which of these theories best explain perceived biodiversity.

4.2 | Association between perceived and actual diversity

We found high associations between perceived and actual diversity for both visual and acoustic stimuli (Figure 1, Step 2). This is in contrast to several studies reporting that participants cannot easily perceive biodiversity (Austen et al., 2021; Dallimer et al., 2012; Phillips & Lindquist, 2021; Rozario et al., 2024; Stobbe et al., 2022). The accuracy of people's diversity estimations, however, might be influenced by whether they rate an environment's diversity alone, or in comparison with other environments. Of the studies that identified discrepancies between perceived and actual diversity, two studies used cross-sectional measurements (Dallimer et al., 2012; Phillips & Lindquist, 2021), while in Rozario et al. (2024), participants were assigned to one environment only. In the present study, however, several forest environments were rated against each other, which enabled participants to directly compare diversity levels. Many studies reporting a good agreement between perceived and actual diversity also allowed participants to directly compare environments (e.g. Gao et al., 2019; Johansson et al., 2014; Simkin et al., 2020; Southon et al., 2018), thus supporting the assumption that the study design might be a crucial factor that determines the accuracy of diversity ratings, and our understanding of perceived diversity.

The accuracy of perceived biodiversity ratings probably also depends on how these perceptions are assessed—whether participants are directed to consider a specific biodiversity indicator, such as species richness, or rate biodiversity more broadly based on their own understanding (Marselle et al., 2015; Rozario et al., 2024). Additionally, the choice of biodiversity indicators used for comparison influences the strength of observed associations between actual and perceived biodiversity. In this study, participants rated forest biodiversity broadly, and these ratings were compared to a composite measure of actual biodiversity, incorporating species richness and structural diversity. However, results showed variation in correlations when considering only one specific biodiversity indicator: Perceived diversity was strongly correlated with forest structural diversity but only moderately with tree species richness (see Appendix S8).

The participants' ability to rate acoustic diversity was slightly stronger than their ability to reflect visual diversity. Compared to the photographs, the audio recordings were quite simple, as they did not contain any other noises when a bird vocalisation was not present. Therefore, the independent variable (bird species richness) was more easily identifiable by the participants. The forest images not only showed variations in tree species richness but also understorey or forest structural attributes and were not otherwise against a blank background, as would be analogous for the acoustic recordings. We reasoned that the value of using stimuli from natural forest settings was more advantageous than less realistic stimuli. However, a replication of this study with simpler visual stimuli, through, for example, depicting only tree species or close-up photos of their twigs against a neutral background (e.g. Austen et al., 2021, 2023; Hofmann et al., 2017), or conversely, more complex acoustic stimuli by combining bird vocalisations with sounds from insects, wind or water would be useful to quantitatively compare the strength of the association between actual and perceived diversity for the two senses.

4.3 | Diversity indices as proxies for perceived and actual diversity

We could identify computed diversity indices that can measure perceived and actual diversity for both the visual and the acoustic sense. For the visual sense, we found a significant positive relationship between the Greenness Index and perceived and actual visual diversity, while the Brightness Index was significantly negatively associated with actual diversity, but not related to perceived diversity (Figure 1, Step 3; Table 4).

Our findings suggest that the Greenness Index probably captures aspects of both perceived and actual visual diversity in forests. The significant positive correlation between the Greenness Index and perceived visual diversity, as well as the importance of vegetation density in the open sorts, suggests that it is the amount of green vegetation that influences perceived visual forest diversity. Research by Dallimer et al. (2012) supports this interpretation: They reported a significant association between the tree cover of riparian areas and perceived species richness. Schebella et al. (2019) further investigated the linkages between biodiversity and mental well-being in urban green spaces, finding that several diversity metrics, including vegetation cover, were significantly associated with well-being. Interestingly, in their study, the well-being effects of naturalness, bird species richness, habitat diversity and structural heterogeneity all became insignificant when controlling for the effects of vegetation cover, thus underpinning the relevance of vegetation for human perception and human–biodiversity interactions more generally (Schebella et al., 2019). Regarding the link between the Greenness Index and actual visual diversity, plant biodiversity is closely linked to ecosystem greenness through its effects on biomass and photosynthetic activity. Higher biodiversity enhances biomass production via mechanisms like niche complementarity, resource partitioning and the inclusion of highly productive species (Isbell et al., 2011; Loreau et al., 2001; Tilman et al., 1996). In addition, biodiverse ecosystems possess greater resistance to environmental fluctuations (Isbell et al., 2011), which results in more stable photosynthetic activity, leading to greener environments.

The negative correlation between the Brightness Index and actual visual diversity indicates that the photographs were darker in plots with higher tree species richness and greater forest structural diversity, also for the understorey. This may be because forests with, for examole, higher tree species richness can have greater canopy packing, and thus less light in the understorey (Jucker et al., 2015).

No association was found between visual indices representing variations of light or colour and perceived diversity. Regarding the brightness indices, one explanation may be that despite being able to recognise variations of light, participants do not necessarily associate this with forest diversity. The Colourfulness Index was also not associated with perceived diversity, although it was frequently cited in the open sorts (Table 2). Our colourfulness values may not have successfully reflected perceived diversity ratings because of the time of year the photographs were taken. Our photos captured in late summer may lack the vibrant colours present in spring and autumn, influenced by flowering plants in the understory and changing foliage. Despite participants observing subtle variations in colour in the open sorts, the Colourfulness Index would have reflected mostly green and therefore likely did not vary sufficiently to significantly reflect variations in biodiversity or participants' perceptions of forest diversity in late summer. Replicating this study at different times of year would more thoroughly address the question of visual indices as proxies for actual and perceived diversity. A cross-seasonal comparison would, for instance, allow for specifically investigating the influence of visual indices within and across seasons. Following our results, it may be possible that greenness is the decisive perceived diversity attribute in summer via different shades of green and in winter through the differentiation between deciduous and evergreen species, while colour may more accurately explain perceived visual diversity in spring via flowers and blossoms and autumn via leaf colours and fruits. A larger study could then compare the influence of greenness and colourfulness for perceived diversity across seasons.

Visual indices derived from photographs represent a static, momentary snapshot of what individuals might perceive in a forest. However, actual experiences in forests create a substantially greater amount of information, influenced by the frequency of saccadic eye movements and the duration of the forest stay. Future studies could address this by employing methods such as eye-tracking glasses with integrated video recording or virtual reality experiments. These approaches would enable the calculation of visual indices from continuous video data, capturing temporal changes in perception and incorporating richer information, thereby enhancing precision and validity.

Regarding acoustic diversity indices, all four indices were significantly correlated with both perceived and actual diversity. This indicates that for the auditory sense, diversity indices are well suited to reflect both people's subjective perception of acoustic diversity and actual bird richness. Interestingly, the correlations between each acoustic index and perceived diversity ratings were descriptively higher than their correlations with actual bird species richness, suggesting that acoustic indices may be more effective in reflecting perceived diversity than actual diversity (although they succeed in significantly reflecting both in the present study). One reason for this may be that acoustic indices tend to level off when more than a handful of species are singing at the same time, which was found for simulated (Gasc et al., 2015) and real soundscapes (Beason et al., 2023). Similarly, human perception of vocalising bird richness may be impeded; the more species sing together and the more birdsongs overlap. Future studies could specifically study soundscapes with high bird richness to see whether perceived diversity ratings reach a plateau when a certain number of birds vocalise together and test whether this pattern aligns with the one seen for acoustic indices.

4.4 | Multisensory biodiversity experiences

Perceiving a forest's biodiversity is of multisensory origin by nature. Yet, there is a pronounced scarcity of scientific evidence for biodiversity-health linkages evoked through senses other than vision and hearing. This necessitates more studies to assess how exactly biodiversity manifests through all five senses and their relevance for the nature-health nexus.

The present study strengthens our understanding of both perceived visual and acoustic biodiversity individually and how these align with actual diversity. Future studies might build upon our findings by testing combined audio-visual perception of biodiversity or even include all five senses and how perceived multisensory diversity mirrors and diverges from actual diversity. To the best of our knowledge, only one study investigated whether perceived diversity differs after exposure to uni- versus multisensory diversity with the result that the unisensory experience of biodiversity resulted in higher perceived species richness (Schebella et al., 2020). Future studies should therefore elaborate on the complex interplay of the human senses in biodiversity experiences, that is, whether the layering of senses would result in antagonistic effects as seen in Schebella et al. (2020) or additive or synergistic effects of sensory stimuli. Understanding how we perceive diversity may then help to design biodiverse healthscapes for wildlife and people alike.

4.5 | Technical limitations

As in many other experimental laboratory studies that involve people as test subjects, the present work also lacks representativeness as mainly highly educated women were tested. Future studies may therefore increase efforts to include a more representative sample to avoid bias resulting from different socio-demographic backgrounds. Our results may, for instance, in part be attributable to the high education levels of our test subjects that may have led to an overrepresentation of knowledge-based ecological phenomena in the sorting criteria (e.g. diurnal bird song activity patterns).

5 | CONCLUSION

Our study provides evidence that perceived and actual diversity are correlated for the visual and acoustic sense. All four computed acoustic diversity indices provide a good proxy for actual and perceived acoustic diversity. For the visual sense, however, only the visual index Greenness reflects actual and perceived visual diversity well. We provide first insights into the nature of perceived visual and acoustic forest diversity, and we suggest conducting more systematic research to quantify the relationship of single forest diversity attributes with perceived diversity while also accommodating for the senses not covered in the present work.

Since perceived visual and acoustic diversity are linked to mental well-being, we recommend conserving and restoring diverse forests characterised by a variety of tree species and high structural diversity to provide habitats for different vocalising bird species. Our findings suggest that these forests are also perceived by people as more biodiverse, probably leading to increased health effects and also meeting conservation goals.

AUTHOR CONTRIBUTIONS

Conceptualisation and Design: Kevin Rozario, Taylor Shaw, Erich Schröger, Melissa Marselle, Rachel Rui Ying Oh and Aletta Bonn; Data collation: Kevin Rozario, Mateo Giraldo Botero; Formal analysis: Kevin Rozario, Taylor Shaw, Valentin Ștefan, Rachel Rui Ying Oh, Melissa Marselle, Mateo Giraldo Botero; Writing—first Draft: Kevin Rozario, Taylor Shaw; Writing—Review and editing: All authors contributed critically to the drafts and gave final approval for publication. Funding acquisition: Aletta Bonn, Bogdan Jaroszewicz, Michael Scherer-Lorenzen and Kris Verheyen.

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CONFLICT OF INTEREST STATEMENT

Aletta Bonn, Melissa Marselle and Rachel Rui Ying Oh are associate editors of *People and Nature*, but were not involved in the peer review and decision-making processes for this paper.

DATA AVAILABILITY STATEMENT

All data are openly accessible at the institutional data repository of the German Centre for Integrative Biodiversity Research (iDiv) (Rozario & Oh, 2025; https://doi.org/10.25829/idiv.3569-j3g2q3).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1: Details on visual stimuli and examples.

Appendix S2: Details on acoustic stimuli.

Appendix S3: Written study instructions.

Appendix S4: Summary of visual and acoustic index values and R code to compute them.

Appendix S5: Correlations between diversity indices.

Appendix S6: First-order clusters of all five raters and their assignment to the second-order clusters.
Appendix S7: Environmental fitting analyses with actual diversity, perceived diversity and the diversity indices.
Appendix S8: Correlation Analyses of tree richness, forest structural diversity, understory structural diversity and understory abundance with perceived visual diversity and the visual diversity indices.
Appendix S9: References.

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