

# Dynamic complexity in audiovisual aesthetics

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AC is supported by the Spanish Ministry of Universities, within the framework of the Recovery, Transformation and Resilience Plan, and funded by the European Union (NextGenerationEU) with the participation of the University of the Balearic Islands. GO is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 864420 - Neurolive).

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All authors approved the final version of the manuscript. Declarations of interest: none.

Data and materials are available at <https://doi.org/10.17605/OSF.IO/E5UH9>.

## Abstract

The appreciation of dance, film and other temporal art forms relies on the continuous integration of auditory and visual streams. In this study, we investigate how bimodal audiovisual preferences arise from unimodal auditory and visual preferences. To this end, we created and validated the open-resource Complexity in AudioVisual Aesthetics (CAVA) stimulus set (<https://osf.io/e5uh9/>), consisting of 120 short, dynamic and abstract auditory, visual and audiovisual stimuli in which auditory and visual complexity corresponds to the number and variety of elements. In Experiment 1, 87 participants rated liking and perceived complexity for each stimulus, with visual, auditory and audiovisual blocks fully randomised. In Experiment 2, 53 participants rated how much they liked each stimulus with the audiovisual block presented first to avoid potential bias arising from prior experience of unimodal stimuli and the simultaneous complexity judgements. Structural equation modelling and linear mixed-effects analysis show that liking for audiovisual stimuli can be explained by a weighted sum of liking for their auditory and visual components modulated by audiovisual congruence. Audiovisual preferences exhibit inverted-U-shaped relationships with auditory and visual complexity, the latter mediated by perceived complexity and modulated by congruence. Our findings provide a carefully controlled departure point for better understanding the role of prediction of sequential structure for the experience of dynamic audiovisual art forms such as dance or film.

*Keywords:* audiovisual, complexity, information content, liking, movement

## Dynamic Complexity in Audiovisual Aesthetics

Most experiences in life are multimodal (Møller et al., 2021; Stein, 2012) and unfold in time (Spence & Squire, 2003; Stevenson & Wallace, 2013). This is especially true for the appreciation of temporal arts such as film, dance or theatre. These art forms involve integrating at least two—auditory and visual—sensory modalities. Film, media and performance scholars have long argued that the appreciation of (e.g., liking for) these art forms relies on the congruence of their structural and semantic unimodal features (Chion, 1994; Cohen, 2013; Jordan, 2011; Tsay, 2013). However, research in audiovisual aesthetics using naturalistic stimuli like dance or film is difficult because their formal features (e.g., auditory and visual complexity) are not easily separated from their semantic features, including narrative or emotional expression through the human body. In the present study, we use carefully controlled non-representational stimuli varying in auditory and visual complexity to address two critical questions: First, we test how liking for audiovisual stimuli relates to liking for their unimodal auditory and visual components. Second, we explore how liking for dynamic audiovisual stimuli relates to objective and subjective complexity measures, introducing new measures for dynamic visual complexity.

### Relationship Between Liking for Audiovisual Stimuli and for their Unimodal Auditory and Visual Components

The Gestalt principle that *the whole is greater than the sum of its parts* refers to the perception of an object or phenomenon being different from the mere addition of its constituent elements (Köhler, 1971; Wertheimer, 1938). In the context of appreciation of

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audiovisual stimuli, it remains unclear how appreciation of bimodal (e.g., audiovisual) stimuli is related to appreciation of its unimodal components. We expect the Gestalt principle to apply, but there are several ways in which it could do so: First, liking for bimodal stimuli might reflect a weighted sum of liking for their unimodal components. Second, the unimodal influences may not be independent but interact. Third, combining auditory and visual components may produce new emergent properties influencing liking for the audiovisual whole.

Research on audiovisual integration provides clues as to how auditory and visual components combine to produce liking for audiovisual stimuli. Audiovisual integration is flexible and adaptive, varying with the relative relevance and reliability of the underlying perceptual components and expectations about the origin and causality of the signal (Meijer et al., 2019; Parise et al., 2012; Rohe & Noppeney, 2018). Spatial and temporal cues influence the relative weighting of visual and auditory information, resulting in the dominance (*capture*) of one kind of information over the other. Examples include *visual capture*—e.g., McGurk (McGurk & MacDonald, 1976; Spence & Soto-Faraco, 2010, for a review) or *ventriloquist effects* (Alais & Burr, 2004)—and *auditory capture*—or *temporal ventriloquism* (Burr et al., 2009; Morein-Zamir et al., 2003). Research suggests preeminence of the auditory stream (auditory capture) when temporal properties are more salient and, conversely, preeminence of the visual stream (visual capture) when spatial properties are more salient. Integration is optimal (Holmes, 2007; Stanford et al., 2005; Stevenson & James, 2009) when the unimodal components share spatial (Meredith & Stein, 1986a, 1996) and temporal (Meredith et al., 1987; Miller & D'Esposito, 2005; Senkowski et al., 2007) sources

—consistent with the *common cause* or *unity assumption* (see Chen & Spence, 2017, for a review)—and when they are similarly salient (Holmes, 2009; Kayser et al., 2005; Meredith & Stein, 1983, 1986b; Perrault et al., 2005). Therefore, an uneven weighting of liking for the unimodal components could point to attention directed to either unimodal component driving liking for the audiovisual composite.

Regarding emerging properties, we focus on congruence between the complexity of the auditory and visual components of audiovisual stimuli. In research on the perception of film music, Lipscomb and Kendall (1996; see also Lipscomb, 2005) proposed that attentional focus is maintained on the audiovisual composite rather than on either unimodal stream in isolation when semantic associations between auditory and visual streams are deemed appropriate based on previous experience and to the extent to which auditory and visual accent structures are consistent. Lipscomb (1999) found support for such structural consistency when using animations by Norman McLaren (corroborated with artificially controlled materials in Lipscomb, 2005) but not when using film extracts. This suggests that the effect may depend on the nature of the material and led the author to call for reliable, quantitative metrics of audiovisual complexity. These ideas have been substantially developed in Cohen's (2013) *congruence-association model*. According to it, semantic and structural relationships between music and visual components of film (also text, speech and sound effects) are initially processed independently, allowing for structural congruence (as investigated here) to be assessed independently from semantic congruence before these components are integrated into a working narrative, which is in turn influenced by expectations derived from long term memory.

## **Relationship between complexity and liking for audiovisual stimuli**

Stimulus complexity influences the experience of both auditory and visual stimuli (Berlyne, 1970, 1971; Chmiel & Schubert, 2017; Nadal et al., 2010). It affects recognition memory (Halpern & Bartlett, 2010), learning (Flagg et al., 1976), physiological arousal (Potter & Choi, 2006) and attention, with auditory dominating visual complexity for attention maintenance (Alwitt et al., 1980; Wartella & Ettema, 1974). Moreover, complexity appears to influence appreciation across cultures, albeit with some elements of cross-cultural variation (Che et al., 2018). Liking has typically been reported to be maximal for stimuli with intermediate complexity (Berlyne, 1970, 1971; Berlyne & Boudewijns, 1971). However, many empirical results deviate from this general trend due to different definitions of complexity, experimental manipulations—including stimuli and measures (Che et al., 2018; Marin et al., 2016; Martindale et al., 1990; Nadal et al., 2010)—and analytical approaches—e.g., whether considering individual or group-averaged responses (Clemente, 2021; Güçlütürk et al., 2016; Marin & Leder, 2018). Regarding dynamic auditory stimuli like music, genuine evidence for negative quadratic relationships between musical complexity and liking constitutes only a minority (26.3%) of the results reviewed by Chmiel and Schubert (2017). It is, therefore, unclear whether complexity and liking for dynamic audiovisual stimuli will display a linear or non-linear (i.e. quadratic) relationship.

The influence of objective, feature-based complexity might be mediated by perceived complexity (e.g., Berlyne, 1971). However, most literature focuses on direct relationships between stimulus properties or their perceptual representations and liking, with scarce counterexamples (e.g., Clemente et al., 2023). Taking subjective ratings of liking and complexity for each stimulus enables a direct and systematic examination of whether perceptual representations of complexity (subjective complexity) mediate the impact of

objective complexity on liking. Our study aims to delineate the relative influence of objective and subjective complexity for dynamic audiovisual stimuli.

## Measures of Auditory, Visual and Audiovisual Complexity

Whereas research on complexity and liking for dynamic auditory or static visual stimuli is relatively widespread, liking for dynamic audiovisual complexity has yet to receive comparable attention. One of the main difficulties in operationalising audiovisual complexity is the need to identify a measure of complexity that can be applied across both auditory and visual streams.

In music and other sound streams, complexity can vary as a result of the *number of tones in a sequence* (Mindus, 1968), *chord structure* (Berlyne et al., 1963), *rhythm and syncopation* (Heyduk, 1975), *structural change* (Mauch & Levy, 2011), *variety in pitch, note durations, loudness and timbre* (Berlyne & Boudewijns, 1971). The Expectancy-based model (EBM; Eerola & North, 2000; Eerola et al., 2006), or Expectancy-violation model (EV; Eerola, 2016), and the MUST<sub>K</sub> model (Clemente et al., 2020) consist of composite measures of weighted structural features that have also been found prominent in the visual modality (Nadal et al., 2010): *number (event density)* and *variety and organization of elements* (computed as different forms of *entropy* in the MUST<sub>K</sub> and *pitch proximity, tonal ambiguity, and rhythmic variation* in the optimal EV models).

While complexity measures are relatively well defined for *static* images (e.g., Fernandez-Lozano et al., 2019; Machado et al., 2015), attempts to develop a formal measure of *dynamic* visual complexity are scarce. Existing tools are highly stimulus-specific and need to be sufficiently validated. For instance, Watt and Welch (1983) measured the visual complexity of children's television programs. In an alternative approach, Kearns and

O'Connor (2004) applied Shannon entropy to calculate moving-image complexity. Finally, Orlandi and colleagues (2020) assessed the dynamic visual complexity of dance movements as entropy characterisations in the context of dance aesthetics. They showed that viewers prefer movements with variable yet predictable changes in speed and acceleration. However, none of these studies address how the complexity of dynamic visual and auditory components might interact.

One way to overcome the modality-specificity of existing complexity measures is to apply information-based theories and models (Kesner, 2014; Koelsch et al., 2019; Van de Cruys et al., 2017; Van de Cruys & Wagemans, 2011). However, to our knowledge, complexity measures based on information-based models of dynamic visual or audiovisual stimuli had yet to be available. The Information Dynamics of Music (IDyOM; Pearce, 2005, 2018) is a well-established framework for investigating the impact of information-theoretic properties on the perception and appreciation of music (Clemente et al., 2020; Sauvé & Pearce, 2019). It is a system for constructing multiple-viewpoint, variable-order Markov models for predictive modelling of probabilistic structure in symbolic, sequential auditory domains like music. IDyOM acquires knowledge about a domain through statistical learning and generates conditional probability distributions representing the estimated likelihood of each event in a sequence, given the preceding context and incremental training on the current stimulus.<sup>1</sup> From the conditional probability estimates for each event, IDyOM computes Shannon *entropy*, which reflects the prospective predictive uncertainty of the model's probabilistic prediction given the context, and *information content*, which reflects the

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<sup>1</sup> In the present research, IDyOM was configured to use a short-term model (STM) only, though it can also be configured to use a separate model given training prior to the stimulus (the long-term model or LTM), often from a large body of stimuli representing the outcome of long-term schematic statistical learning. The STM and LTM can also be combined in the BOTH configuration.



contextual unpredictability of the event that actually follows from the model's perspective. Although no information-based complexity model existed for *dynamic* visual or audiovisual stimuli, IDyOM's architecture is flexible enough to enable the computation of information-theoretic measures of any sequence of discrete events. Here, we used IDyOM to quantify auditory complexity and, for the first time, dynamic visual complexity, providing comparable and generalisable measures of dynamic auditory and visual complexity.

## **Aim and Hypotheses**

Our overarching aim was to investigate liking for dynamic audiovisual displays in relation to the complexity of their auditory and visual components. Specifically, our first goal was to test the hypothesis that liking for the audiovisual whole is greater than the plain sum of liking for the unimodal components. Our second goal was to unveil the structure of relationships between stimulus complexity, perceived complexity and liking for dynamically time-varying audiovisual stimuli.

To this end, we first created a novel stimulus set of dynamic unimodal and bimodal stimuli varying parametrically in auditory, visual and audiovisual complexity, respectively. Then, we ran two experiments: Experiment 1 investigated links between objective and subjective complexity measures and how they relate to liking. Experiment 2 replicated Experiment 1 in an in-person setting and established a direct link between objective complexity and liking, eliminating two potential confounds: First, bimodal stimulus blocks were always presented before unimodal blocks to avoid priming of bimodal preferences by the prior rating of unimodal preferences. Second, participants rated only liking to prevent influence of concurrently rating perceived complexity on liking ratings.

To address our two main goals, we ran two analyses: First, we tested the hypothesis conforming to the Gestalt principle that the whole is greater than the (plain) sum of its parts (Köhler, 1971; Wertheimer, 1938) (Experiments 1 and 2) and examined the nature of the relationship between liking for audiovisual stimuli and liking for the unimodal components. We expected that liking for the auditory and visual components would differently influence liking for the audiovisual composite and a moderating role of audiovisual congruence. Second, we tested the hypothesis of a mediating role of perceived complexity on the impact of stimulus complexity on liking (Experiment 1). In addition, we expected negative quadratic effects of auditory and visual complexity on liking.

## Method

### Participants

In both experiments, native English speakers from the general population were unaware of the study's purpose and reported normal or corrected-to-normal vision and hearing and no cognitive impairments. Ethical approval was granted by the Psychology department at Goldsmiths, University of London.

Previous research using mixed-effects models with random effects per participant and stimulus consistently employed sample sizes of around 40 participants (e.g., Clemente et al., 2021, 2022b; Corradi et al., 2020). Following recommendations for online studies (Sauter et al., 2020; Stewart et al., 2017), we doubled this sample size. According to Judd and colleagues' (2016) power calculator ([https://jakewestfall.shinyapps.io/two\\_factor\\_power/](https://jakewestfall.shinyapps.io/two_factor_power/)), both experiments—in which all participants rated 120 stimuli on each scale—would have a

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power of 1 for a moderate effect size of 0.5, which was expected by default given the lack of previous research with our experimental manipulations. In Experiment 1, 90 participants were recruited through Prolific (<https://www.prolific.co/>) with a minimum approval rate of 80% and compensated for participation following Prolific recommendations. Three participants with missing or invalid data were consequently excluded from the analyses. In Experiment 2, 53 UK residents took part and were compensated with £5.

We used the Goldsmiths Musical Sophistication Index (Gold-MSI; Müllensiefen et al., 2014) *general factor* scale to characterise the sample emulating the distribution in the general population. The demographic data distributions in the final sample (Table 1) approach those in the general population (age median = 40.50, 50.57% women, 49.43% men, UK, 2022<sup>2</sup>).

Table 1. *Demographic Data*

Experiment	<i>N</i>	Age (range, <i>M</i> , <i>SD</i> )	Gender (w, m, other)	GoldMSI (range, <i>M</i> , <i>SD</i> )
1	87	[19, 68], 34.15, 11.88	45, 40, 2	[48, 99], 70.24, 9.96
2	53	[20, 61], 29.64, 8.53	29, 24, 0	[35, 120], 77.51, 21.77

*Note.* GoldMSI refers to the score in the *general factor* scale.

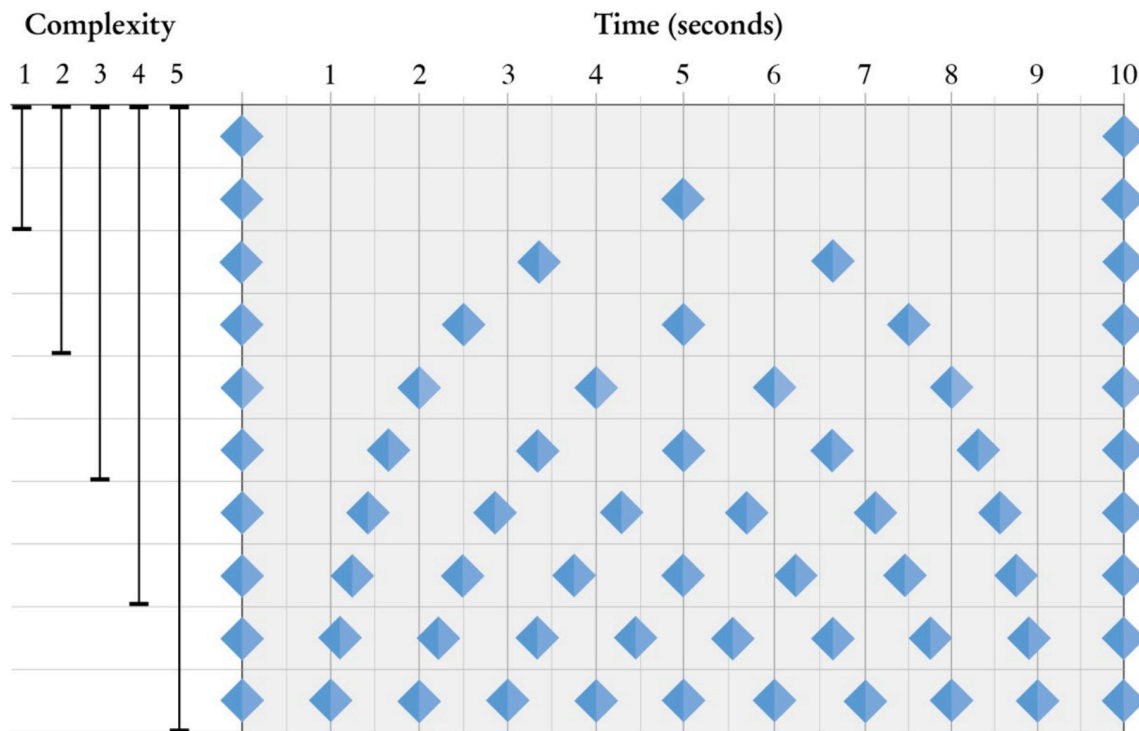
## Stimuli

A novel set of 120 non-representational 10-second stimuli was created: the complexity in audiovisual aesthetics (CAVA) stimulus set consists of auditory, visual and

<sup>2</sup> Source: <https://www.statista.com>

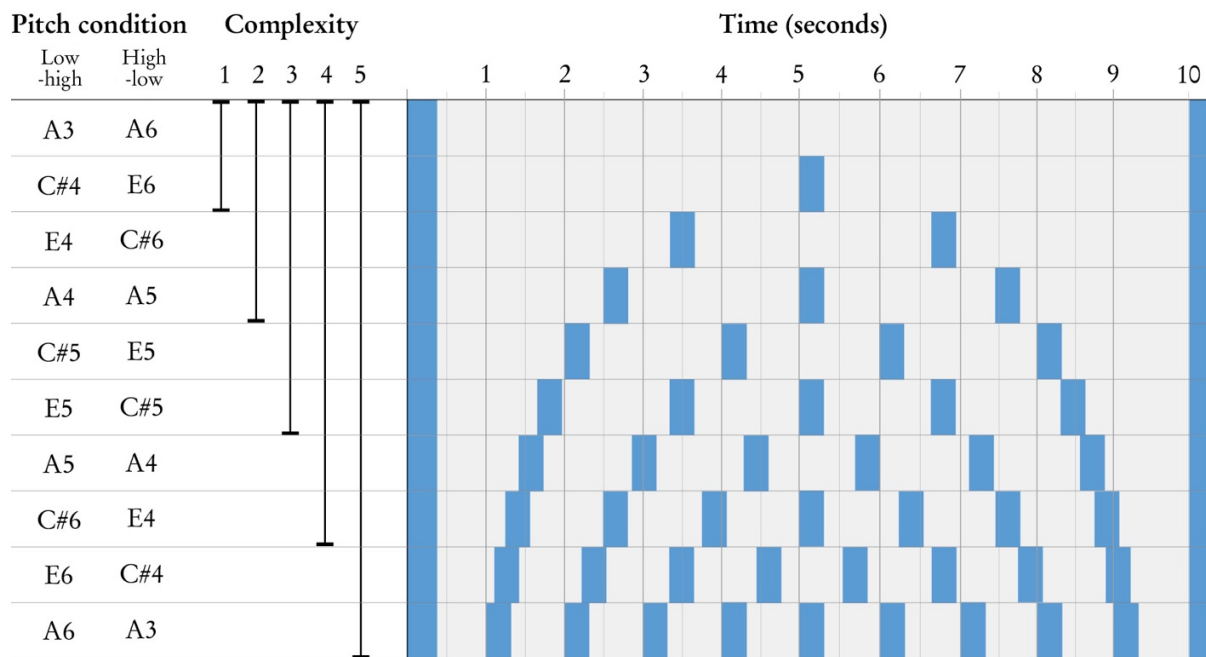
audiovisual sequences varying in complexity. Complexity was manipulated by systematically increasing the number (event density) and variety of elements (modality-specific variability between events) (Nadal et al., 2010) in the auditory and visual modalities separately, as described below. The CAVA set is publicly available as an open resource for research at <https://osf.io/e5uh9/> in MOV and MP4 formats.

The visual stimuli (V) consist of white horizontally moving vertical lines on a black background, inspired by McLaren and Lambart's (1960) abstract animation *Lignes Verticales*. The number of lines (event density) and velocities (modality-specific variability) determine feature-based complexity in the visual modality. Five feature-based complexity levels were defined. The simplest visual stimulus contains two moving lines: The first line completes a horizontal journey from one side to the other for the duration of the video (0.1 Hz). The second line makes a return trip horizontally across the screen, thus travelling twice as fast (0.2 Hz). The most complex sequence contains ten moving lines, the fastest travelling ten times (1 Hz) across the screen. Therefore, each feature-based complexity level increases the number of lines by two, resulting in 2, 4, 6, 8, or 10 lines for each level (1–5). In addition, each level is presented in two movement directions: In LR, lines move from left to right, whereas in RL, they move from right to left. This results in ten visual stimuli (Figure 1) created using Adobe After Effects CC2018.



*Figure 1.* Visual sequence structure. Each row represents a vertical line. Stimuli of a given complexity level include the corresponding vertical lines indicated on the left of the figure. Diamonds on the far left indicate a line leaving one side of the display at the beginning of the stimulus, while diamonds on the far right indicate a line arriving at the same side of the display at the end of the stimulus. Diamonds at intermediate time points indicate a line arriving at one end of the display and leaving in the opposite direction. For example, the first row indicates a vertical line that started on one side of the visual display and arrived at the other side 10 seconds later, while the second row indicates a vertical line that starts on one side of the visual display, arrives at the other side 5 seconds later and returns to the original side after 10 seconds. A stimulus with a complexity level of 1 comprises both these lines presented simultaneously.

The auditory stimuli (A) were designed to replicate the structure of the visual stimuli mapped into the auditory domain. They consist of 0.35-second sine tones belonging to the A-major triad in the range A3–A6. Each stimulus comprises between two and ten pitches, each of which sounds repeatedly with a specific period. Thus, the number of sounds (event density) and pitches (modality-specific variability) constitute feature-based complexity in the auditory modality. Five auditory feature-based complexity levels (1–5) were defined: The simplest sequence comprises two pitches and five events. The most complex sequence comprises ten pitches distributed across 65 events. Each complexity level is presented in two pitch directions: In LH, the pitches proceed from low to high, whereas in HL, they proceed from high to low. This results in ten auditory stimuli (Figure 2) created using Adobe Audition CC2018.



*Figure 2.* Auditory sequence structure. Each horizontal row is dedicated to a particular pitch sounding with a particular periodicity, as indicated by the blue (dark) rectangles, each of which represents the timing of a sine tone with the corresponding pitch class (A, C#, E) and octave designation (3–6). A stimulus of a given complexity level includes the corresponding pitches (rows) indicated on the left of the figure. Two versions of the stimuli are provided: the high-low condition in which higher pitches are more frequently repeated, and the low-high condition in which lower pitches are more frequently repeated—given the symmetric (mirror-like) structure of the stimuli. For example, in the low-high condition, the first row indicates an A3 that sounds at 0 and 10 s, while the second row indicates a C#4 that sounds at 0, 5 and 10 s. A stimulus with complexity level 1 includes the pitches indicated on the first two rows of the figure presented simultaneously.

The ten auditory and ten visual sequences were orthogonally combined to produce 100 audiovisual stimuli in Adobe Premier Pro CC 2018. Therefore, each audiovisual stimulus is characterised by a specific degree of congruence between auditory and visual complexity: minimal when the feature-based complexity levels are most dissimilar and maximal when

these levels are the same in both sensory modalities. Furthermore, because the auditory and visual stimuli followed the same principles of rhythmic construction (cf. Figures 1 and 2), audiovisual congruence entails synchrony, in the sense that each visual event (a line reaching the frame of the screen) occurs at the same time as the corresponding auditory event (a sine tone) and vice versa.

The stimuli conform to, or leverage, the three principles of optimal multimodal integration (Chen & Spence, 2017; Holmes, 2007; Stanford et al., 2005; Stevenson & James, 2009): First, they originate from the same source, the laptop, complying with the spatial rule (Meredith & Stein, 1986a, 1996). Second, they involve perfect synchrony between the beginning and end of the auditory and visual streams when congruence is high, accommodating the temporal rule (Meredith et al., 1987; Miller & D'Esposito, 2005; Senkowski et al., 2007). Third, by combining visual and auditory components with greater or lesser degrees of congruence in complexity, they vary in compatibility with the inverse-effectiveness rule (Holmes, 2009; Kayser et al., 2005; Meredith & Stein, 1983, 1986b; Perrault et al., 2005).

## Measures

We manipulated feature-based complexity as the number (event density) and variety of elements (modality-specific variability between events) (Nadal et al., 2010) in each sensory modality over time. This was achieved by varying event density and event variability while orthogonally contrasting presentation modes (H–L vs L–H pitch and R–L vs L–R line movement direction). However, this feature-based operationalisation of complexity is limited because it is, by definition, specific to the features manipulated—which may not be present in



other stimuli. Furthermore, neither event density nor event variability reflects the complexity

		Auditory complexity				
		-		+		
Visual complexity	-	0	0.25	0.50	0.75	1
		0.25	0.50	0.75	1	0.75
		0.50	0.75	1	0.75	0.50
		0.75	1	0.75	0.50	0.25
	+	1	0.75	0.50	0.25	0

of the sequential configuration of the stimulus.

Therefore, we measured information-based complexity by developing Information Dynamics of Music (IDyOM; Pearce, 2018) models of the auditory and visual streams. Information-based complexity measures are not only sensitive to the number and variety of elements but also the sequential structure of the stimuli. Therefore, they are more generalisable to other kinds of discrete sequential stimuli. In this context, the auditory stimuli can be represented as sequences of sound events differing in pitch, while the visual stimuli can be represented as sequences of visual events (line arrivals at one side of the display or the other) differing in movement velocity. Sequences of auditory and visual events with the same complexity level have identical timing.

Among the IDyOM information-based measures available, information content was preferred over entropy on theoretical grounds—it reflects the unpredictability of actual events rather than the model’s prospective predictive uncertainty given the context—and on practical grounds—it has been used successfully as the main information-theoretic complexity measure in previous research (Cheung et al., 2019; Clemente et al., 2020; Gold et al., 2019; Sauvé & Pearce, 2019), which affords comparison across studies. The feature-based and information-based measures used in this research accompany the CAVA stimulus set.

To assess congruence, we subtracted from 4 the absolute value of the difference between the auditory and visual complexity levels and divided by 4 to normalise in the range

from 0 (indicating least congruence) to 1 (indicating perfect congruence). Therefore, although the scale is continuous and comparable to the complexity measures, its levels are categorical and were treated as such in the analyses (Table 2).

Table 2. *Audiovisual Congruence Levels*

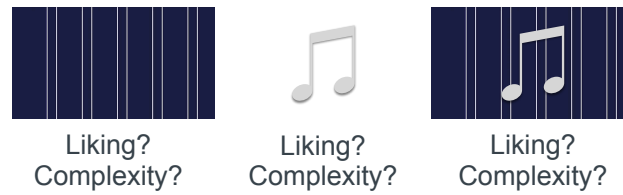
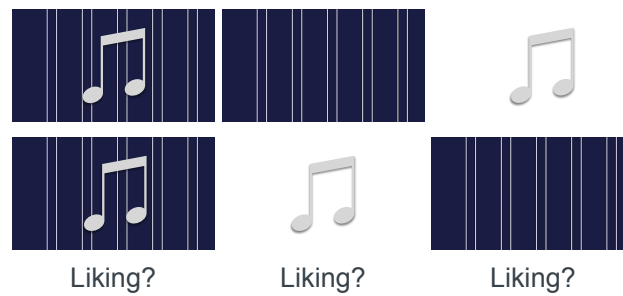
Note. Auditory complexity increases from left (very simple) to right (very complex). Visual complexity (V) increases from down (very simple) to top (very complex). Numbers denote audiovisual complexity congruence from 0 to 1.

The CAVA set in MOV and MP4 formats and the corresponding feature-based and information-based measures are publicly available as open resources for research at <https://osf.io/e5uh9/>. Detailed validation analysis is provided as supplemental material (SM). The results show that our systematic manipulation captured participants' abilities to perceive and appreciate different levels of auditory complexity and show a nearly perfect correlation between information-based and feature-based complexity measures. Importantly, all three measures of complexity (feature-based, information-based and perceived) predicted liking for audiovisual stimuli, and neither line movement direction (L–R or R–L) nor pitch movement direction (H–L or L–H) predicted liking.

## Procedure

In Experiment 1, participants completed the online experiment created and hosted using Gorilla Experiment Builder (<https://www.gorilla.sc>; Anwyl-Irvine et al., 2018). After providing informed consent, prospective participants performed a browser soundcheck, a built-in volume calibration and a headphone screening (Milne et al., 2020). Block (auditory, visual and audiovisual) order was counterbalanced across participants, and stimulus order was individually randomized for each participant (Figure 3). A 1-s fixation cross preceded each visual and audiovisual stimulus. Immediately after stimulus presentation, participants rated their liking for each stimulus on a 7-point Likert scale anchored by *dislike a lot* (1)

and *like a lot* (7) and how complex they perceived the stimulus to be on a 7-point Likert scale anchored by *very simple* (1) and *very complex* (7). They were instructed to make judgments quickly and intuitively and encouraged to use the full range of each rating scale. Following the rating blocks, the participants completed the Musical Sophistication Index general factor scale (Gold-MSI; Müllensiefen et al., 2014), an abridged version incorporating aspects from all five sub-scales. Finally, participants provided basic, customary demographic data (age and gender). Participants were allowed to take breaks between blocks but were required to complete the experiment in a single session, which took about 40 minutes.

**E1 Counterbalanced block order****E2 AV blocks before A&V blocks**

*Figure 3.* Design of Experiment 1 (E1) and Experiment 2 (E2). AV stands for audiovisual A for auditory and V for visual.

In Experiment 2, participants were tested individually on site. The experiment was conducted on a 15-inch MacBook Pro using PsychoPy2 version 1.85.4 (Peirce et al., 2019). All participants sat approximately 50 cm from the experimenter's laptop, were undisturbed during the experimental session and listened to the audio and audiovisual stimuli through ATH-R70x headphones with the volume set at a comfortable level. The stimuli, questionnaires, measures and experimental paradigm were identical to Experiment 1 except for two differences: First, we only collected liking ratings to prevent any influence of perceived complexity on liking. Second, the bimodal block always preceded the unimodal blocks to prevent a direct influence of unimodal on bimodal liking ratings. The order of auditory and visual blocks was counterbalanced across participants (Figure 1). Therefore, Experiment 2 was conducted in a more controlled setting, restricted to liking ratings to avoid any potential confounding effects of taking simultaneous complexity ratings and prevented

the experience of the audiovisual stimuli from being biased by prior experience of the unimodal stimuli.

## **Data Analysis**

### **Relationship between liking for audiovisual stimuli and for their unimodal auditory and visual components.**

We analyse data in Experiment 1 and Experiment 2 separately using linear mixed-effects modelling (Hox et al., 2010; Snijders & Bosker, 2012), following Barr and colleagues' (2013) recommendation to model the maximal random-effects structure justified by the experimental design. We compare four models: Model #1 reflects bimodal audiovisual preferences as the sum of unimodal auditory and visual preferences. Model #2 retains the summative analysis but allows for weighted contributions of auditory and visual preferences. Model #3 adds congruence to the weighted sum without interactions. Model #4 introduces interactions between congruence and liking for each component. Therefore, Models #1–2 test for simple or weighted additive linear effects, whereas Models #3–4 test for the contribution of an emerging property, congruence, in addition or interaction with such additive effects.

All models include intercepts and slopes per participant and intercepts per stimulus as random effects to account for the variability within and between participants and stimuli. To examine the relevance of such variability, we test whether removing fixed and random effects from each model in a stepwise model reduction improves the model fit through likelihood-ratio tests. Otherwise, we prefer the saturated model. For statistically significant differences ( $p < .05$ ), lower Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) indicate a better fit to the data of one model over another. In cases of conflicting

criteria, Vrieze (2012) and Yang (2005) recommend prioritising AIC over BIC. Finally, we compare the best-fitting models #1–4 following the same procedure.

All analyses are performed within the R environment for statistical computing, R version 4.2.3 (R Core Team, 2023). For the mixed-effects models, we use the `lmer` function in the ‘lme4’ package (Bates et al., 2015) and the ‘lmerTest’ package (Kuznetsova et al., 2017) to estimate the  $p$ -values for the  $t$ -tests based on the Satterthwaite approximation for degrees of freedom, which produces acceptable type-I error rates (Luke, 2017). We report the model  $r^2$  for fixed effects only (*marginal*) and fixed plus random effects (*conditional*) regarding each response variable in the preferred model in each Experiment and interpret them according to Chin (1998). Effect sizes are calculated using the `effectsize` function in the ‘effectsize’ package (Ben-Shachar et al., 2020) and are interpreted following Gignac and Szodorai’s (2016) recommendations.

### **Relationship between complexity and liking for audiovisual stimuli.**

We analyse data in Experiment 1 using structural equation modelling (SEM) to test for a mediating effect of perceived complexity on the relationship between the stimulus properties and liking in the context of audiovisual stimuli varying in complexity. Following the rationale above, the internal models making up the SEM involve random effects per participant and stimulus, and the variables are not assumed to be normally distributed. Therefore, we apply *piecewise SEM* (or *confirmatory path analysis*; Shipley, 2009), which expands upon traditional SEM by introducing a flexible mathematical framework that can incorporate a variety of model structures, distributions and assumptions, including interactions, non-Gaussian responses, random effects, hierarchical models and alternate correlation structures.

We compare models with linear and quadratic terms to test for the inverted-U-shaped

relationship between complexity and liking (Berlyne, 1971; Chmiel & Schubert, 2017; Nadal et al., 2010). Then, a stepwise model reduction is conducted for each configuration, starting with the following fixed-effects structure in R syntax, while the random effects have the

```
form(1|stimulus)+([fixed]|participant):
```

```
perceivedComplexity ~ auditoryIC + visualIC + auditoryIC:congruence +  
    visualIC:congruence
```

```
liking ~ perceivedComplexity + auditoryIC + visualIC + congruence +  
    auditoryIC:congruence + visualIC:congruence
```

Each SEM is adjusted according to three parameters: unsaturated model (non-significant paths to test the SEM fit:  $df > 0$ ), global goodness of fit (sufficiently low  $C$ :  $p > .05$ ) and absence of missing paths (tests of directed separation:  $p > .05$ ). We implement the SEM analysis using the `psem` and `plot` functions in the ‘piecewiseSEM’ package (Lefcheck, 2016), version 2.3.0. The `psem` output includes unstandardised and standardised estimates for each predictor (allowing comparisons within and between models), statistical significance and coefficients of determination reported and interpreted as in the previous section.

## Results

### Relationship Between Liking for Audiovisual Stimuli and for their Unimodal Auditory and Visual Components

Removing effects (whether predictors, interactions or random effects) significantly worsens the model fit (all  $ps < .01$ ). Consistently across experiments, the model of liking as a function of aggregated liking for the unimodal stimuli is outperformed by the model allowing for different weightings. The model fit is further improved when introducing congruence and

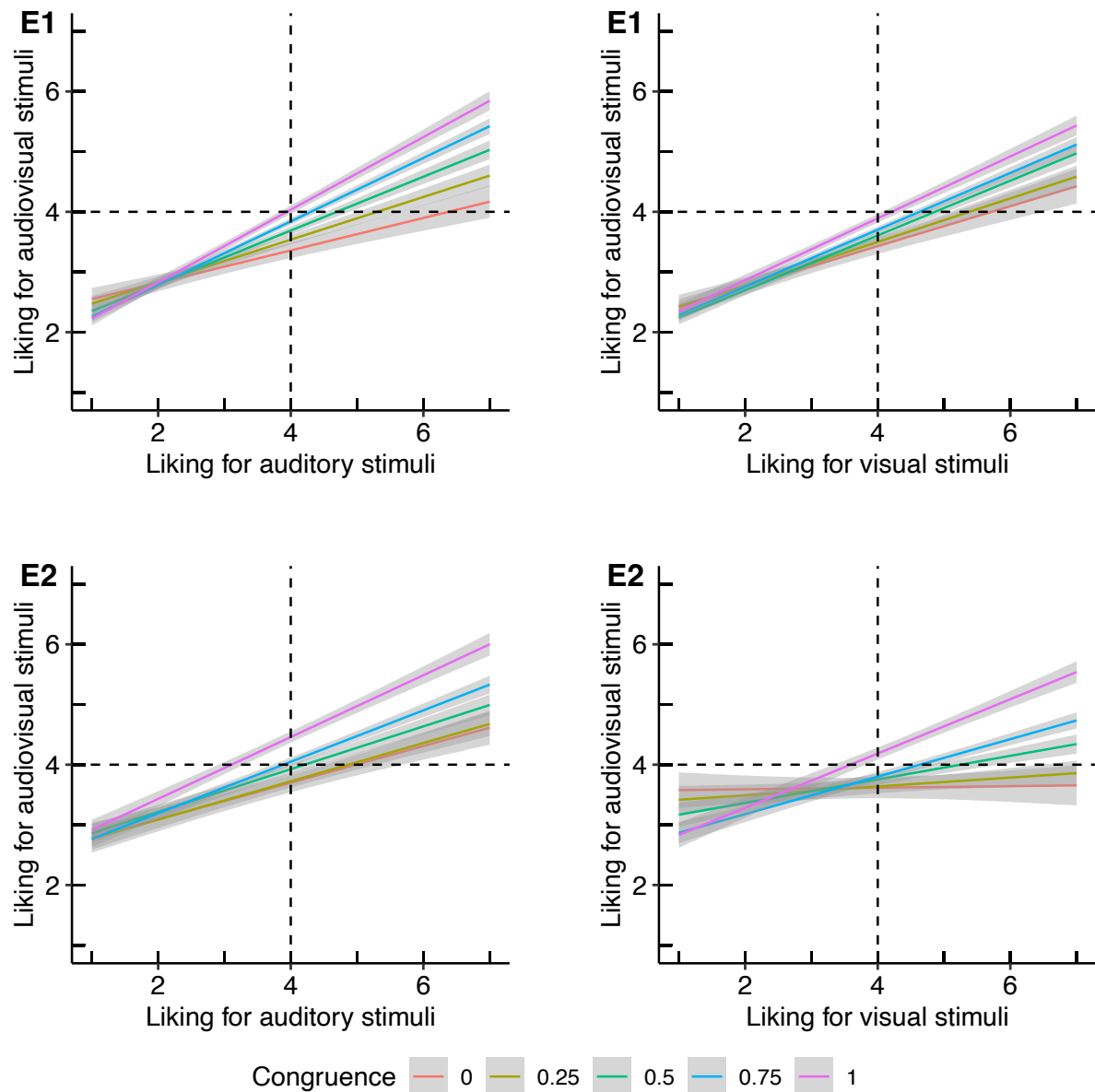


is finally surpassed by the model considering interactions between congruence and liking for each unimodal component (Table 3, Figure 4).

Table 3. *Models of Liking For Audiovisual Stimuli as a Function of Liking for Auditory and Visual Stimuli and Audiovisual Congruence*

E	M	Model configuration of fixed effects in R syntax	AIC	BIC	$\chi^2$	df	p
1	1	I(a.liking + v.liking)	26538	26587			
	2	a.liking + v.liking	25985	26063	560.52	4	< .01
	3	a.liking + v.liking + c	25866	25979	129.59	5	< .01
	4	<b>a.liking + v.liking + c + a.liking:c + v.liking:c</b>	<b>25852</b>	<b>25979</b>	<b>17.49</b>	<b>2</b>	<b>&lt; .01</b>
2	1	I(a.liking + v.liking)	18934	18980			
	2	a.liking + v.liking	18684	18756	257.98	4	< .01
	3	a.liking + v.liking + c	18568	18673	126.09	5	< .01
	4	<b>a.liking + v.liking + c + a.liking:c + v.liking:c</b>	<b>18559</b>	<b>18677</b>	<b>12.74</b>	<b>2</b>	<b>&lt; .01</b>

*Note.* ANOVA mixed-model likelihood ratio tests of different configurations of models (M) of liking for the audiovisual stimuli as a function of liking for their auditory (a.liking) and visual (v.liking) streams and congruence (c) in each experiment (E). The configurations represent the fixed effects of the model equation in R syntax. Akaike (AIC) and Bayesian (BIC) information criteria for each model are reported together with the statistics of the multiple comparisons in each Experiment:  $\chi^2$ , degrees of freedom (df) and p-value. Preferred models are highlighted in bold.



*Figure 4.* Liking for audiovisual stimuli as a function of liking for their auditory (left) and visual (right) components in Experiment 1 (E1, top) and 2 (E2, bottom) for each congruence level. Although the direction of the effects of congruence are consistent across Experiments and unimodal stimuli, they only reach significance for auditory stimuli in Experiment 1 and for visual stimuli in Experiment 2. Dashed black lines represent neutral ratings in the Likert scale. Shaded areas represent 95% CI.

Across experiments, the best-fitting model reveals that liking for audiovisual stimuli is positively associated with liking for the corresponding unimodal stimuli. Audiovisual congruence shapes how much audiovisual liking is explained by liking for the unimodal

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components, as it boosts the effect of liking for auditory stimuli in Experiment 1 and that of liking for visual stimuli in Experiment 2 (Table 4).

Table 4. *Best-fitting Model of Liking for Audiovisual Stimuli as a Function of Liking for Auditory and Visual Stimuli and Audiovisual Congruence*

E	$r^2_m$	$r^2_c$	Fixed effects in R syntax	$\beta$	$df$	$t$	$p$	$d$ [95% CI]
1	.12	.58	<b>a. liking</b>	<b>0.13</b>	<b>186.88</b>	<b>3.92</b>	<b>&lt; .01</b>	<b>0.20 [0.15, 0.25]</b>
			<b>v. liking</b>	<b>0.18</b>	<b>141.03</b>	<b>5.17</b>	<b>&lt; .01</b>	<b>0.20 [0.14, 0.26]</b>
			congruence	-0.12	381.32	-0.66	0.51	0.08 [0.03, 0.12]
			<b>a. liking: congruence</b>	<b>0.12</b>	<b>2588.31</b>	<b>4.08</b>	<b>&lt; .01</b>	<b>0.04 [0.02, 0.05]</b>
			v. liking: congruence	0.04	1323.46	1.19	0.23	0.01 [-0.01, 0.03]
2	.18	.37	<b>a. liking</b>	<b>0.28</b>	<b>133.35</b>	<b>7.11</b>	<b>&lt; .01</b>	<b>0.33 [0.26, 0.40]</b>
			<b>v. liking</b>	<b>0.08</b>	<b>155.86</b>	<b>2.20</b>	<b>&lt; .01</b>	<b>0.17 [0.12, 0.23]</b>
			congruence	-0.10	502.94	-0.36	0.72	0.12 [0.06, 0.17]
			a. liking: congruence	0.04	2639.75	1.02	0.31	0.01 [-0.01, 0.04]
			<b>v. liking: congruence</b>	<b>0.14</b>	<b>4281.42</b>	<b>3.50</b>	<b>&lt; .01</b>	<b>0.04 [0.02, 0.07]</b>

*Note.* Estimated effects of liking for auditory (a.liking) and visual (v.liking) stimuli and audiovisual congruence.  $r^2_m$  refers to marginal and  $r^2_c$  to conditional coefficient of determination,  $\beta$  to the unstandardised estimate,  $df$  to degrees of freedom,  $t$  to  $t$ -value,  $p$  to  $p$ -value and  $d$  to effect size in each experiment (E). Significant effects are highlighted in bold.

## Relationship Between Complexity and Liking for Audiovisual Stimuli

SEM analyses are conducted to examine whether perceptual ratings of complexity mediate the relationship between stimulus complexity measures and liking. The models with linear predictors fail to converge. The model with the following structure in R syntax yields the best fit to the data ( $AIC = 53284.34$ ;  $\chi^2 = 2.20$ ,  $p = 0.53$ ,  $df = 3$ ;  $C = 10.95$ ,  $p = 0.09$ ,  $df = 6$ ):

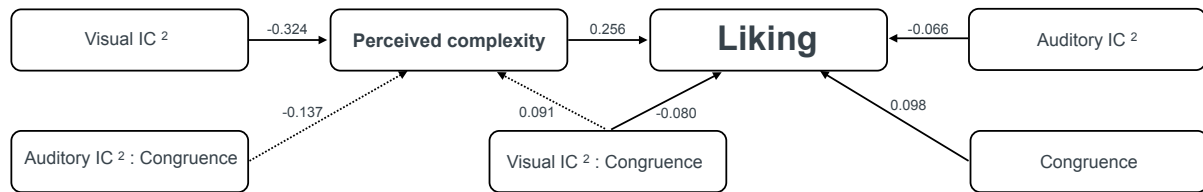
perceivedComplexity ~ visualIC<sup>2</sup> + auditoryIC<sup>2</sup>:congruence + visualIC<sup>2</sup>:congruence  
 liking ~ perceivedComplexity + auditoryIC<sup>2</sup> + congruence + visualIC<sup>2</sup>:congruence

Perceived complexity follows a negative quadratic relationship with visual IC. Liking is positively associated with perceived complexity, follows a negative quadratic relationship with auditory IC, increases with congruence and follows a negative quadratic relationship with visual IC moderated by congruence. In other words, auditory IC and congruence directly affect liking, whereas the effect of visual complexity on liking is partially mediated by perceived complexity and moderated by congruence (Table 5, Figure 5).

Table 5. *Models in the Structural Equation Model (SEM) of Liking for Audiovisual Stimuli*

Response	$r^2_m$	$r^2_c$	Predictor	$b$	$se$	$df$	critical value	$p$	$\beta$
perceived complexity	.08	.65	<b>visual IC<sup>2</sup></b>	<b>-0.71</b>	<b>0.19</b>	<b>103.25</b>	<b>-3.64</b>	<b>&lt; .01</b>	<b>-0.32</b>
			auditory IC <sup>2</sup> : congruence	-0.40	0.21	98.31	-1.90	.06	-0.14
			auditory IC <sup>2</sup> : congruence	0.28	0.30	96.81	0.94	.35	0.09
liking	.10	.54	<b>perceived complexity</b>	<b>0.24</b>	<b>0.01</b>	<b>4833.18</b>	<b>22.67</b>	<b>&lt; .01</b>	<b>0.26</b>
			<b>auditory IC<sup>2</sup></b>	<b>-0.13</b>	<b>0.05</b>	<b>133.35</b>	<b>-2.72</b>	<b>.01</b>	<b>-0.07</b>
			<b>congruence</b>	<b>0.53</b>	<b>0.14</b>	<b>122.51</b>	<b>3.78</b>	<b>&lt; .01</b>	<b>0.10</b>
			<b>visual IC<sup>2</sup> : congruence</b>	<b>-0.23</b>	<b>0.08</b>	<b>141.97</b>	<b>-2.98</b>	<b>&lt; .01</b>	<b>-0.08</b>

Note.  $r^2_m$  stands for marginal and  $r^2_c$  for conditional coefficient of determination,  $b$  for unstandardised estimate,  $se$  to standard error,  $df$  for degrees of freedom,  $p$  for  $p$ -value and  $\beta$  for standardised estimate. Significant effects are highlighted in bold.



*Figure 5.* Structural equation model (SEM) representing the structure of relationships between auditory and visual quadratic information content (IC<sup>2</sup>), audiovisual congruence, perceived complexity and liking for audiovisual stimuli. Solid arrows denote a significant impact of one variable on another ( $p \leq .05$ ). Dashed arrows depict non-significant associations ( $p > .05$ ) necessarily included in the SEM—as removing them from the individual models would worsen the model fit, eliminating the degrees of freedom required to evaluate the global SEM. Numbers represent standardised estimates.

## Discussion

We created, validated and made publicly available a new stimulus set and generalisable measures of auditory and visual dynamic complexity. These tools allowed us to investigate two important aspects of audiovisual aesthetics. First, we tested the Gestalt principle that the whole is greater than the sum of its parts in the context of liking for audiovisual stimuli varying in auditory and visual complexity. Second, we examined the relationship between stimulus properties, their perceptual representations and liking for audiovisual stimuli varying in auditory and visual complexity.

The results of the validation analysis (see supplemental material) suggest that the CAVA set has good construct validity in systematically manipulating perceived auditory, visual and audiovisual complexity, and support the use of information-based measures over feature-based measures. Extending IDyOM model to dynamic visual information provides a

meaningful and generalisable quantification of information-based complexity to study the structural complexity of audiovisual stimuli.

The results of the model comparisons addressing our first research question suggest that liking for audiovisual stimuli can be explained as a weighted additive function of liking for both unimodal components, distinctly moderated by audiovisual congruence: It enhanced the effect of liking for the auditory component when perceived complexity was overtly rated (Experiment 1), whereas it enhanced the effect of liking for the visual component when complexity was not explicitly rated (Experiment 2).

Several implications are worth considering here: First, the moderating role of congruence supports the Gestalt principle that the whole is greater than the (plain) sum of its parts (Köhler, 1971; Wertheimer, 1938) in that the contributions of each component are not identical and that an emergent property (congruence between auditory and visual complexity) exerts a moderating influence on such contributions sensitive to the context of evaluation. This entails shifts in the relative importance of each unimodal component, which aligns with capture effects (Spence & Squire, 2003; Stevenson & Wallace, 2013). Second, people do not usually experience auditory and visual components separately before experiencing the audiovisual whole, and smaller effects of liking for the unimodal components in Experiment 1 than in Experiment 2 suggest some mitigation by concurrent complexity ratings. In this sense, Experiment 2 more closely resembles liking for audiovisual stimuli in the real world. In this case, the results indicate a closer link between congruence and visual complexity or a greater malleability of the visual than the auditory component. Third, the differences between the impact of auditory and visual complexity on perceived complexity and liking and their relations with congruence align with distinct processing of auditory and visual streams (Griffin et al., 2002; Macaluso et al., 2004; Peretz & Coltheart, 2003; Peretz & Zatorre,

2005). Fourth, the susceptibility to context (i.e., presentation order and concurrence of evaluative judgements) concurs with current knowledge on sensory valuation, fruit from the interplay of subject, object and context (Skov, 2019).

The results of the SEM addressing our second research question also suggest distinct effects of auditory and visual complexity and a moderating role of audiovisual congruence on visual complexity: Liking for audiovisual stimuli increased with perceived complexity—which in turn increased for intermediate visual complexity—, intermediate auditory complexity, and congruence between auditory and visual complexity, which was enhanced for intermediate visual complexity. Thus, the results support an inverted-U-shaped relationship between auditory complexity and liking for audiovisual stimuli (Berlyne, 1970, 1971), in line with predictive processing theories of appreciation (e.g., Van de Cruys et al., 2022).

Together with the previous analysis, the results also suggest that visual complexity might be more directly relevant to perceptual evaluation of complexity, while auditory complexity might be more directly relevant to liking. The explanation for these observed modality differences is unclear. We might speculate that unpleasant auditory stimuli would be more difficult to ignore than unpleasant visual stimuli, leading to a greater effect of auditory complexity on liking. Furthermore, participants may be more familiar with processing dynamic auditory stimuli than dynamically time-varying visual stimuli in everyday life, so variations of complexity in dynamic visual components could have been more salient than variations of complexity in the auditory components and had a greater effect on complexity ratings. However, before such speculations can be tested, research is required to corroborate or contest these findings with other dynamic audiovisual stimuli.

Audiovisual congruence (Cohen, 2013; Lipscomb, 1999, 2005) is for the current stimuli equivalent to the simultaneous occurrence of lines and sounds, in keeping with the temporal (Meredith et al., 1987; Miller & D'Esposito, 2005; Senkowski et al., 2007) and inverse-effectiveness rules (Holmes, 2009; Kayser et al., 2005; Meredith & Stein, 1983, 1986b; Perrault et al., 2005; Stanford et al., 2005) of audiovisual integration (Spence, & Squire, 2003; Stevenson & Wallace, 2013). Correspondence between temporal structures allows inferring the environmental source causing the sensory data (Parise et al., 2012; Senkowski et al., 2007) so that perfectly or highly aligned visual and auditory streams contribute to a unitary, coherent and fully integrated percept, facilitating processing fluency (Chenier & Winkielman, 2009; Reber, 2012; Reber et al., 2004; Schwarz et al., 2020). The results suggest that congruence amplifies the impact of liking for the unimodal components (Experiment 1) and visual complexity (Experiment 2) on liking for audiovisual stimuli. This finding advances our understanding of how perceptual and evaluative judgments are distinct albeit related cognitive processes (Jacobsen & Höfel, 2003).

The role of perceptual representations of stimulus properties on the relationship between those properties and appreciation has only started to be systematically examined (e.g., Clemente et al., 2023, 2024). The results of the SEM support a mediating role of perceived complexity on the effects of visual complexity on liking. This finding concurs with those regarding other domains and stimulus properties (e.g., visual contour in Clemente et al., 2023) and supports the role of personal and contextual factors in evaluative judgments (Skov, 2019). Perceived complexity was the main predictor of liking for audiovisual stimuli, showing preeminence of subjective over objective complexity in appreciation (Van Geert & Wagemans, 2020). However, it is plausible that the effects were somehow inflated as judgments of complexity and liking were given concurrently.



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Across models, analyses and experiments, the largest proportion of the variance was explained by the random effects and removing them worsened the fit to the data. This means that accounting for variability between and within participants and stimuli was essential for examining liking for audiovisual objects and the role of stimulus and perceived complexity in liking. This fact underscores the paramount relevance of individual differences in perceptual and evaluative judgments and the need to place them at the centre of empirical investigation (Clemente, 2021; Corradi et al., 2020). Since the vast majority of studies on perception and appreciation typically disregard such variability as noise, reinterpretation of existing research might be advisable.

## Limitations and Future Work

Besides those already acknowledged, we highlight some methodological limitations here. First, our CAVA stimulus set manipulates dynamic auditory and visual complexity using simple visual shapes and sine tones. Importantly, however, the CAVA stimulus set is based on genuine abstract audiovisual artworks and is thus relevant and ecologically valid as a model for non-representational audiovisual art forms, including non-narrative dance (Howlin et al., 2020). While we view this as a useful starting point, further research is needed to understand the role of dynamic visual and auditory complexity in the appreciation of naturalistic stimuli. A recent and relevant example in this vein is Frame et al.'s (2023) study investigating crossmodal influences on appreciation when presenting naturalistic auditory and visual stimuli simultaneously. This study differed from the present research in that the visual stimuli were static images (of artworks) and, therefore, did not have a dynamic temporal structure that could be aligned (or misaligned) with the auditory stimulus; the results showed

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independent additive contributions of auditory and visual pleasure ratings on pleasure for the audiovisual whole. Other studies have shown that music biases emotional responses to dance movements (Christensen et al., 2014; Reason et al., 2016), but hearing the sounds that dancers produce (e.g., footsteps and breathing) can reduce liking for the same dance movement despite meeting all criteria for optimal audiovisual integration (Jola et al., 2014; Orgs & Howlin, 2020). Conceivably, perceived meaningfulness (Martindale, 1990) of audiovisual congruence can outweigh the importance of structural complexity when people appreciate representational audiovisual artworks like film, theatre or dance. Our new dynamic measure of visual complexity could be developed to distinguish the relative contribution of syntactic (dynamic audiovisual complexity) and semantic (narrative or storyline) features to further the understanding of the appreciation of these art forms.

Second, although these experiments systematically manipulated dynamic feature-based complexity across modalities and linked it with information-based complexity in the CAVA set, the relationship between feature-based complexity and information content and their contribution to liking may differ for other stimuli. Therefore, generalising the present experimental approach to other bimodal stimuli is critical. In addition, auditory and visual complexity could be characterised in other ways. For instance, intermittent dots instead of moving lines would be more directly comparable to the pitches in the auditory modality. That said, we did not find an influence of pitch or line movement direction on liking for audiovisual displays, suggesting that specific low-level visual or auditory features are less important than the higher-level attributes of complexity or congruence.

Lastly, the samples were characterised in terms of musical but not visual sophistication, and we did not manipulate domain-specific expertise systematically. Nonetheless, domain-specific expertise is known to affect the role of complexity in liking

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(Hekkert & van Wieringen, 1996; Lahdelma & Eerola, 2020; Orr & Olson, 2005; Popescu et al., 2019; Skov & Kirk, 2021). Therefore, future research should investigate the impact of visual and musical sophistication and other relevant traits on the relationship between complexity and liking for bimodal stimuli.

## Conclusion

The present research investigates the role of complexity and the relationships between stimulus complexity and perceived complexity in liking by systematically manipulating comparable auditory and visual dynamic complexity. In so doing, we contribute a novel stimulus set and generalisable computational measures of auditory and visual dynamic complexity, all of which are available as open resources for research at <https://osf.io/e5uh9/>. We found that liking for audiovisual stimuli can be explained as a weighted combination of liking for its auditory and visual components moderated by audiovisual congruence depending on the relative salience of perceived complexity. Furthermore, liking is maximal for intermediate levels of auditory and visual complexity, the latter mediated by perceived complexity and enhanced by congruence. Crucially, the most variance was explained by variability due to participants and stimuli, highlighting the importance of considering individual differences.

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