

Hearing Brightness

Multidisciplinary Perspectives on a Ubiquitous Attribute of Timbre and Orchestration

CHARALAMPOS SAITIS, KAI SIEDENBURG, AND MOE TOUIZRAR

STANLEY Kubrick's 1968 sci-fi masterpiece, *2001: A Space Odyssey*, opens with a sequence that has since become iconic: a majestic cosmic sunrise set to the opening fanfare of Richard Strauss's *Also sprach Zarathustra*.¹ The character of the fanfare, titled "Sonnenaufgang" (Sunrise), is undeniably expansive and bright. But the precise source of our sensation of sonic brightness is difficult to pinpoint (see Figure 12.1): is it the timbre of the trumpets, the repetition and specific articulation of a rising C-G-C motive, the dramatic terracing and swelling of dynamics, or perhaps the progressive re-voicing and re-orchestration of the punctuated chordal complex? Put generally and more concisely, how do timbre and orchestration contribute to the phenomenon of sonic brightness, and where is brightness to be located within experience? In this chapter, we attempt to articulate and distinguish between two modes: *timbral brightness* (the psychophysical perception of brightness in a given instance of sound) and *orchestral brightness* (the experience of brightness in the configuration and unfolding of orchestral music). We approach the central questions from a multidisciplinary vantage, attempting to hold any tensions between the two modes without resolution.

The sensation of brightness is generally familiar to listeners, and the properties of sound that we might categorize as timbral are often characterized in terms of brightness. Timbre, as Emily I. Dolan (2013) demonstrates, first entered musical discourse only recently—around the turn of the eighteenth century. In the first edition of the *Dictionnaire de l'Académie française* (1694), "timbre" is defined in the context of a bell's sound. By the third edition of the *Dictionnaire* (1740), the notion of timbre had evolved to describe the quality of sound, its definition expanded to tell us that often a bell's timbre could be "too bright,"² signaling an important early recognition of brightness as a distinguishable attribute of timbre—but not the earliest. In *De Audibilibus*, Naomi Weiss (2018) informs us, Pseudo-Aristotle³ describes how "the brightest [*lamprotatos*] sounds are those that are best able to move the sense of hearing

¹ All three authors contributed equally.

² "Il se dit quelquefois, pour Le son que rend le timbre. Ce timbre est trop éclatant." "Timbre," in *Dictionnaire de l'Académie française*, 3rd ed., 2 vols. (Paris: Jean-Baptiste Coignard, 1740), vol. 2, 770.

³ The authorship of *De Audibilibus* is uncertain; it was formerly attributed to Aristotle, but modern scholars have variously ascribed it to Theophrastus, Heraclides Ponticus, and Strato of Lampsacus (Gottschalk 1968; Barker 1990, 98–109).

3 Oboes
 1 Clarinet in Eb; 2 Clarinets in Bb
 3 Bassoons; 1 Contrabassoon
 4 Horns
 4 Trumpets
 3 Trombones

Sehr breit. ($\text{♩} = 69$)

Winds
 Brass
 Perc.
 Strings

+ 3 Flutes
 + 1 Piccolo
 + 2 Horns (6 in total)
 + 2 Bass Trombones

Winds
 Brass
 Perc.
 Strings

Downloaded from <https://academic.oup.com/edited-volume/626001/chapter/560522276> by OUP-Reference Gratis Access user on 21 April 2026

FIGURE 12.1 Reduction of “Sonnenaufgang” from Richard Strauss’s *Also sprach Zarathustra*, mm. 1–19 with corresponding stills from Stanley Kubrick’s *2001: A Space Odyssey*.

when they impinge on it.⁴ Here, the adjective *lamprotatos* appears to denote the specific quality of a sound, not so much its pitch or volume, but rather the radiant light of the sound itself—its timbre. That is to say, there was a brightness before timbre,⁵ a way of negotiating tone quality before timbre became a more defined concept, first through bells and soon after by Rousseau in Diderot's *Encyclopedie* (1765a, 1765b), as a property of sound discrete from pitch and loudness. Crucially, Rousseau defined timbre as “the quality [of sound] which is always subject to the comparison between dullness and brightness, or between harshness and softness,”⁶ thereby also defining a specifically timbral perception of brightness.

The perception of timbral brightness is rooted in the psychophysical properties of sound waves and how they are processed by the auditory system. Brightness in this sense can be correlated with the spectral content of a sound, particularly the presence and emphasis of higher frequencies. We understand orchestral brightness as referring to the ways in which different instruments, melodies, harmonies, and rhythms interact over time to create a unified perception of musical brightness. In certain cases, brightness can lead to a phenomenological experience of sonic luminosity—as if sound becomes light. Beyond the technical realms of frequency and waveform, orchestral brightness becomes a bridge between the composer's intent and the listener's perception. This duality of understanding—perceiving brightness in isolated sounds versus experiencing the rich tapestry of brightness in orchestral music—invites an outward-looking and multidisciplinary exploration of what it means to engage with musical brightness. The ideal starting place for locating brightness as it relates to the perception of instrumental timbre is in the experimental psychology literature. The ideal starting place for locating conceptions and formulations of orchestral brightness is within orchestral repertoires, where the curious depiction of light by composers is not only commonplace but relatively understudied. The authors' aim is not to answer any questions definitively, nor to synthesize or reconcile positions, but rather to draw on our respective disciplinary knowledge and skill sets—including music theory, composition, acoustics, and psychology—to provide multiple, often contrasting perspectives and spark conversation across different fields of study, anticipating productive “science frictions” along the way (Edwards et al. 2011).

Perceptual Foundations: A Tale of Two Methods

Timbre is widely agreed to be a multi-faceted percept—it is thought of as any property other than pitch, duration, and loudness that allows two sounds to be distinguished—and so two prevailing approaches to the study of timbre perception have sought to decompose the timbre gestalt into its constituent elements.

⁴ “τὸν αὐτὸν τρόπον τῶν φωνῶν ταύτας ὑποληπτέον εἶναι λαμπροτάτας, ὅσαι μάλιστα δύνανται προσπίπτουσαι κινεῖν τὴν ἀκοήν, Ps. Arist. *De Audib.* 801b25–27, as cited and translated by Weiss (2018, 240).

⁵ Here, we reference the title of Deirdre Loughridge's chapter in *The Oxford Handbook on Timbre* (Loughridge 2018, 269), “Timbre Before Timbre,” itself referring to what Emily I. Dolan has called “a time before timbre” (Dolan 2013, 14).

⁶ “la qualité du timbre qui est encore susceptible de comparaison du sourd à l'éclatant, ou de l'aigu au doux” (Rousseau 1765a, 345–347).

Perceptual Dimension and Semantic Attribute of Timbre

Concerning perceptual dimensions of timbre, one set of studies has started from constructing “timbre spaces.” These are geometrical configurations resulting from multi-dimensional scaling (MDS) (Shepard 1962) of dissimilarity ratings for pairs of sounds (for more detail and a recent review see McAdams 2019). MDS generates a spatial configuration of points whose pairwise distances approximate the original perceptual dissimilarity data. In order to rule out potential confounds from other attributes, sound stimuli are usually equalized in pitch, loudness, and duration (and presented over headphones or a speaker, thereby removing any differences in spatial position) before entering a dissimilarity rating design. The central assumption of MDS studies is that shared psychophysical dimensions exist according to which the tested sounds can be ordered. Concerning semantic attributes of timbre (a second major approach to timbre), research begins by applying dimensionality reduction techniques such as exploratory factor analysis (EFA) and principal components analysis (PCA) to construct semantically labeled timbre spaces from ratings of sound stimuli along verbally anchored scales (for more detail and a comprehensive review see Saitis and Weinzierl 2019). Semantic scales are typically constructed either by two opposing descriptive adjectives such as “bright” and “dull” (known as the semantic differential method; see Osgood 1952) or by an adjective and its negation as in “bright” and “not bright” (known as the verbal attribute magnitude estimation method; see Kendall and Carterette 1993). Each semantic scale is thought of as capturing an experiential continuum, or geometrically as a straight line that passes through the origin of a Euclidean spatial configuration of the tested timbres. By assuming that many different continua are psychologically close and may hence be represented by a single latent dimension, EFA and PCA can both recover the minimum number of such dimensions, which are generally orthogonal to each other. Similar to MDS studies, sound stimuli are usually equalized in pitch, loudness, and duration before entering a semantic rating design.

Today, a number of MDS studies using real recordings or synthetic emulations of orchestral instrument notes have confirmed that the attack time and the spectral centroid of musical tones constitute major acoustical correlates of timbre spaces (Grey 1977; McAdams et al. 1995). Attack time is defined as the logarithm of the duration between the onset of a sound and its more stable part. The spectral centroid (SC) is defined as the amplitude-weighted mean frequency and can be interpreted as the center of gravity of the spectral envelope or the frequency that divides the spectrum into two regions with equal energy (Caetano, Saitis, and Siedenburg 2019). The timbre space dimension most strongly correlated with the spectral centroid is then considered as reflecting timbral brightness. Convergent evidence from many “timbre semantics” studies (as they came to be known) using recorded or synthesized orchestral sounds have further confirmed that the SC dimension of timbre is captured by adjectives such as *bright* or *brilliant* (high SC values) and *dull* or *dark* (low SC values). Yet spectral envelopes of sounds can vary in manifold ways, certainly more than can be exhaustively described by the one dimension of the SC (Saitis and Siedenburg 2020). For instance, using synthetic tones with formant-like characteristics, Siedenburg (2018) demonstrated consistent shifts of perceived brightness between tones with highly similar SC values. In the semantic space of Zacharakis, Pasiadis, and Reiss (2015), the brightness dimension was related to both energy distribution of the partials and spectral detail. This echoes earlier work by Boring and Stevens (1936), who found an inverse relationship between brightness and density in complex but also pure (i.e., single-frequency) tones. Spectral bandwidth has also been found to be of relevance to brightness judgments (Rosi et al. 2023). Could timbral brightness

be a lump sum of multiple psychoacoustical cues that are collectively associated but might separate if considered in greater detail?

The Role of Temporal Cues and Sound Source Categories

To answer this question, Saitis and Siedenburg (2020) studied timbral brightness using the same empirical framework as general timbre perception, namely, instructing listeners to rate how dissimilar two instrumental sounds are with respect to brightness. Using MDS analysis, the authors found that brightness dissimilarity ratings could be adequately described on the basis of a single dimension correlated with the SC of the tested stimuli. This dimension further correlated strongly with the SC dimension of a general dissimilarity space derived from the same stimuli and with their ordering obtained from direct brightness ratings. Such triangulation of evidence confirmed that, however incomplete the SC may be, it may still act as an effective summary descriptor for quantifying timbral brightness perception. Interestingly, when a two-dimensional MDS space was examined to model the brightness dissimilarity ratings, a dimension related to attack time emerged alongside the SC dimension. This is in line with reports that when asking listeners to explain impressions of brightness in musical sounds, references to the attack of the sound will typically come up (Drouzas and Saitis 2020; Rosi et al. 2022). Saitis et al. (2019) investigated the role of attack transients in timbral brightness perception using synthesized harmonic sounds carefully controlled along three disassociated temporal and spectral envelope parameters: SC, attack time, and variation of SC over the first 100 milliseconds of the sound. The latter models the progressive expansion of the spectrum toward the higher harmonics, also known as harmonic rise asynchrony (Caclin et al. 2005). Results showed an influence of asynchrony in the rise of harmonics: when two sounds with identical spectral centroids and attack times varied in the “arrival” of higher-harmonic energy, faster appearing upper harmonics tended to lead to higher brightness ratings. Attack time did not seem to single-handedly affect brightness ratings, echoing findings by Brent (2010) and Bell (2015), who both reported brighter percussive timbres to be associated with higher SC values during attack while faster attack times were associated with sharper or harder percussion sounds.

Timbre perception naturally associates continuously varying “low-level” properties of an acoustic waveform, transformed into a sensory representation available to the listener, to more “cognitive” categories of sound source-cause inferred from the sensory representation and stored in long-term memory. There is evidence that general timbre dissimilarity ratings, typically assumed to rely primarily on low-level acoustical cues, are in fact susceptible to the formation of source-cause categories (Siedenburg, Jones-Mollerup, and McAdams 2016). For example, a marimba tone and a vibraphone tone (played at the same pitch and loudness and for the same duration) tend to be rated as more similar in terms of general timbre than would be predicted given their acoustic differences, likely a result of listeners “recognizing” that both are percussion instruments and excited in identical ways. Given the many configurational and dimensional similarities shared between perceptual and semantic timbre spaces (Faure, McAdams, and Nosulenko 1996; Zacharakis, Pasiadis, and Reiss 2015), it is reasonable to ask whether comparing two instrumental sounds on a semantic attribute such as brightness could be open to source-cause biases too. Saitis and Siedenburg (2020) found that adding binary descriptors that coded an instrument’s family, source, and excitation mechanism did not improve correlations between observed brightness dissimilarity ratings and their predictions from using only scalar descriptors of the acoustic signal. This “robustness” against source-cause categories suggests that timbral brightness perception is anchored primarily in low-level acoustical cues.

Effects of Adaptation

We all know what it is like to enter a particularly dark or bright room, often requiring one to wait a while until vision adapts to the new normal. And the same light source can be perceived as either dim or bright, depending on the context. In the auditory domain, it would seem reasonable if perception was similarly adaptive. Following this rationale, Siedenburg, Jacobsen, and Reuter (2021) studied whether brightness judgements adapt over time to a given context. Continuous speech or natural music signals were filtered such that sounds varied on a continuum from dark to bright. The experiment had listeners decide on a trial-by-trial basis whether a presented sound was rather bright or dull. Context effects were experimentally studied on two different time scales using a local context that determined whether the previous trial was dark or bright, and a global context that determined whether a full experimental block was rather dark or bright. For both types of contexts, listeners showed significant adaptation effects: a neutral sound was perceived as brighter if the trial was preceded by a dark context and vice versa. In this sense, the observed effect resembled previous findings on auditory contrast enhancement (Holt 2005; Stilp et al. 2010). Computational modeling further suggested that brightness adaptation levels off after around fifteen seconds. This implies that brightness adaptation is not solely based on peripheral adaptation (Dau, Püschel, and Kohlrausch 1996), which is known to act on a sub-second level, but most likely involves both peripheral and central processes. Taking the paradigm one step further toward real-world applications, that study also showed that such adaptation effects persist when stimuli are processed with the acoustic transfer functions of industry-made “hearables” (i.e., headphones that amplify sound of the environment). That is, the *constancy* of sound that is technologically mediated is to some extent guaranteed by processes of brightness adaptation, which allows listeners to “forget” to some extent about the medium and focus on the content.

Is It Timbre? A Tale of Two Qualia

Whether orchestral, electronic, or popular music, brightness differences often happen with simultaneous variation in pitch. Because the pitch dimension is also such a crucial parameter in music, composers and orchestrators will rarely think about brightness in an entirely pitch-independent way. Any account of musical brightness perception thus needs to address the way in which the perception of pitch and brightness interact with and influence each other. There are reasons to expect interactions between the two attributes. The perceptual representation of pitch involves both a linear dimension of “height” related to fundamental frequency (F_0) and a circular dimension of “chroma” related to F_0 position within the octave (Shepard 1964; Ueda and Ohgushi 1987). Pitch height depends more on the spectral envelope (Patterson, Millroy, and Allerhand 1993), which also determines brightness. Thus it could be that the two attributes are not entirely distinct. A considerable body of literature accordingly demonstrates consistent interactions between brightness and pitch perception from across diverse methodological viewpoints.

Interaction Effects between Brightness and Pitch

Most studies of timbre dissimilarity and semantics have used musical instrument tones played at the same pitch (as in F_0) and loudness in order to focus listeners on timbral relations. However, some dissimilarity studies have included sounds varying in pitch and

found that instruments keep their relative positions within timbre space at pitches differing by as much as a major seventh (Marozeau et al. 2003), but that interactions between pitch and timbre appear when tones differ by more than an octave (Miller and Carterette 1975; Marozeau and de Cheveigné 2007; Zacharakis, Pasiadis, and Reiss 2015). These interactions affect the resulting timbre space in two ways. First, a dimension correlated with F_0 and orthogonal to the other dimensions appears. Second, pitch differences systematically influence the dimension that is related to the spectral centroid, that is, brightness. Semantic studies with musical tones played at several pitches further show a positive correlation of F_0 with ratings of brightness (though see Hayes, Saitis, and Fazekas 2022). However, the degree of correlation considerably varies across groups of listeners with different degrees of music and audio expertise (e.g., engineers can be “immune” to it but not conductors, see Rosi et al. 2023) or drawn from different linguistic populations (e.g., it seems stronger for native Greek versus English speaking listeners; see Zacharakis, Pasiadis, and Reiss 2014). For non-expert listeners particularly, F_0 can play a dominant role in explaining brightness ratings (Reymore et al. 2023; Rosi et al. 2023).

Drawing from early work on multidimensional perceptual processing (Garner and Felfoldy 1970), Melara and Marks (1990) studied the interaction of timbral brightness with pitch. The authors had participants conduct speeded classification of sounds as *twangy* versus *hollow* with concurrent variation in F_0 during experimental blocks. They found that concurrent variation in pitch led to increasing reaction times. Interactive dimensions were conceptualized to exhibit links at some level of perceptual processing such that information in one perceptual channel (e.g., pitch, associated with a primary physical dimension such as frequency) were thought to be weighted by information in another channel. Interaction effects thus suggest failures of selective attention, that is, participants’ inability to sufficiently separate information in different perceptual channels, so-called *Garner interference*. Pitt (1994) extended this work by offering four response categories (instead of two), such that participants reported whether they heard changes in pitch, changes in brightness, changes in both pitch and brightness, or no changes at all. Musician participants were highly accurate in their responses. However, accuracy of non-musicians declined markedly for conditions with only brightness change, as well as those where both brightness and pitch changed, which were frequently confused with the other response category involving only brightness change.

An important and more recent approach relied on discrimination tasks to study the interaction between pitch and brightness (Allen and Oxenham 2014). The authors first measured difference limens (DL; also known as just-noticeable differences) for individual F_0 and SC dimensions for musician and non-musician participants, before going on to study interactions with stimulus dimensions equalized according to the individual DLs measured before. Using digitally generated harmonic tone complexes that varied in terms of F_0 and SC position, musicians’ and non-musicians’ DLs were similar for SC changes, but musicians had lower DLs for F_0 changes. A second experiment measured DLs with concurrent variation in SC. With pitch as target dimension, musicians showed clearly the least interference effects. However, there were no differences between listener groups when the relation of the interference was considered, that is, the ratio between DLs for conditions with variation and the DLs for conditions without variation. A third experiment indeed showed that non-musicians had considerably more difficulties to process incongruent changes of F_0 and SC, and particularly incongruent pitch changes were discriminated poorly at larger F_0 /SC intervals between the baseline and target stimuli. In a more recent study using a similar experimental paradigm on an online sample of largely non-musician listeners, Saitis and Wallmark (2024) reported similar pitch-brightness interactions. Notably, they found that the effect of congruency on response accuracy was much larger than on reaction time (38% error when classifying pitch,

20% when classifying brightness). Additionally, participants' accuracy did not decrease as a function of speed (i.e., there was not a significant speed-accuracy tradeoff). This indicates that perceptual acuity in pitch judgment was not affected by additional deliberation time, contrary to much of the literature on crossmodal interactions (e.g., Arieh and Marks 2008), suggesting that participants genuinely confused SC for pitch.

Note that with respect to the spatial representation of pitch height, results have been found that illustrate the interconnected effects in pitch and brightness perception. In Western culture, it is quite natural to associate “high” pitches with high spatial elevation. This association turns out to be strong in Western musicians and parallels the way Western musical notation represents pitch (Pratt 1930; Rusconi et al. 2006). Both phenomena might be grounded in the statistics of natural auditory scenes (Parise, Knorre, and Ernst 2014). Yet, more recent work further suggests that non-musicians only exhibit such spatial association effects for frequency changes consisting of coupled pitch and brightness shifts, but not for one-dimensional shifts alone (Pitteri et al. 2017). This was nicely expressed in the title of the latter study, “Naturally together: pitch-height and brightness as coupled factors.” Taken together, these findings suggest that there certainly exists interference between pitch and brightness for musicians and non-musicians but that this interference is stronger for non-musicians, suggesting that it requires specific training to perceptually tease apart pitch and brightness.

Effects of Context: Contour Processing and Shepard-Illusion

The perception of sound sequences is another topic that has been scrutinized empirically and that bears important implications for orchestration studies. In his reasoning about *Klangfarbenmelodie* (tone-color-melody or timbral melody)—the organization of timbral progressions or “melodies,” Schoenberg explicitly alluded to musical principles (or “logic”) governing the sequential ordering of sounds that differ in timbre. A central question here concerns whether the musico-perceptual principles of *Klangfarbenmelodie* would need to be different for sequences of sounds differing in pitch. Modern empirical studies of sequence processing have indeed noted striking similarities in the perception of sequences of sounds differing in pitch and brightness. McDermott, Lehr, and Oxenham (2008) found that the processing of contours (i.e., the patterns of ups and downs) is comparable when contours are generated by changes in pitch, brightness, or loudness. Notably, familiar musical tunes could even be recognized according to brightness or loudness contours. Asking participants to discriminate sequences of varying length, Cousineau et al. (2014) observed that participants' accuracy for pitch and brightness sequences, but not loudness sequences, decreased very similarly when sequences became longer, also suggesting similar perceptual processes. Siedenburg and McAdams (2018) studied the recognition of timbre sequences with consecutive changes in pitch. In this study, sounds did not only vary according to brightness but were emulations of acoustic instrument sounds. It was observed that non-musicians performed better for sequences with constant pitch compared to sequences with variable pitch, and this effect was not as pronounced for musician participants. In this sense, these results were consistent with the higher interference of pitch and timbre already mentioned above.

A final line of evidence on the relation between pitch and brightness perception has used modified Shepard tones. Shepard tones are sounds with octave-spaced partial tones that are weighted in amplitude by one common amplitude envelope, going back to the innovative work of Roger Shepard and the perception of pitch circularity (Shepard 1964). Extending this idea toward sonic brightness, Siedenburg (2018) used cyclic spectral envelope components

and a fixed fundamental frequency, showing that frequency shifts of the envelopes are perceived as systematic shifts of brightness. Effects of context were observed that were completely analogous to prior work using classic Shepard tones (Chambers et al. 2017), adding to the wide-reaching commonalities between pitch and brightness perception. Siedenburg, Graves, and Pressnitzer (2023) went one step further and studied consecutive pitch and brightness shifts of stimuli varying in spectral envelope and F_0 using a unified auditory modeling framework. The authors suggested that listeners use a compound perceptual dimension that encompasses what is classically called pitch and brightness to achieve the ecological task of tracking frequency change across sounds. Differences in the weighting of acoustic cues across groups of musicians and non-musicians (Schneider et al. 2005) might then be at the perceptual basis of the interference of pitch and brightness noted above.

Acoustical Roots of Auditory Brightness

Whereas the previous section reviewed evidence for interactive processing of pitch and timbral brightness, the reasons underlying such interactions remain unclear. In fact, there could be multiple reasons for this type of interactive processing: Interaction could happen on a sensory level, on an acoustical level from which it is learned through exposure, or both. Relatively little research has considered the potential acoustical origins of pitch-brightness associations. Siedenburg and colleagues (2021) mapped out the relationship of spectral centroid (SC) and fundamental frequency (F_0) in a large set of acoustical instrument sounds, spanning twelve instrument classes with sounds from fifty different orchestral instruments. Different patterns of F_0 -SC covariance arose, depending on the instrument class. For instance, whereas the vocals, saxophones, bassoons, and tubas show relatively little dependence of F_0 at the *ff* level, there was a close correlation for the strings, flutes, recorders, and some brass instruments (although not necessarily across all of their F_0 registers). Almost all instrument classes showed consistent effects of F_0 in two or more registers. There were only a few exceptions to this rule, namely the vocals, saxophones, and bassoons, which did not show F_0 effects in the majority of registers. Highly consistent effects on SC were yielded by the factor of dynamic level (*pp*, *mf*, *ff*), where increased playing effort is consistently associated with higher SC (with the exception of the flutes). The instrument size factor, for which size approximations were taken from the literature, heavily depended on the instrument. Strangely, for the saxophone class, shorter tube lengths (i.e., instruments) did not yield brighter tones with higher SCs in all registers. For instance, the soprano saxophone yielded among the least bright sounds of the family across different dynamic levels (likely because the low register of the soprano sax requires less effort and strain compared to the same pitch played in the higher register of the baritone sax, and thus fewer high partials are present). Other classes such as the strings showed a size-dependency as expected with larger instruments yielding darker tones with smaller SCs.

Given the close covariance of F_0 and SC in naturalistic sounds from acoustical instruments, would it be appropriate to consider auditory brightness simply as an attribute accompanying pitch perception or does it have an acoustical basis independent of fundamental frequency? This question was approached by Jacobsen and Siedenburg (2024) in an analysis/synthesis approach that aimed to characterize the very basic acoustical ingredients of brightness perception. A set of around 1,900 orchestral sounds were analyzed in terms of its main underlying acoustical dimensions, obtained using PCA of a representation of the sound spectral envelope (SE). The first dimension of the resulting space showed a clear low-pass/high-pass characteristic, sharing around 50 percent of the variance of the data.

The second dimension was interpreted as encoding the vowel-likeness of sounds. A perceptual experiment then presented sounds resynthesized along the first and second dimension of the space, using a fixed F_0 (alongside with other conditions). Participants were asked to rate the brightness of sounds. The experiment confirmed that the first dimension of the SE space correlated with brightness ratings, whereas the second dimension did not. The fact that the first and most important dimension of a space of SEs of musical instrument sounds maps onto auditory brightness shows that brightness is not merely an invention of auditory scientists playing around with synthetic sounds, but that it has direct acoustical correlates in the statistics of natural sounds. By means of cross-cultural comparisons, research on music perception has witnessed several suggestive examples of evidence for learning of spectral sound statistics and its direct effects on auditory perception in recent years. This includes examples of consonance perception (McDermott et al. 2016) and octave equivalence (Jacoby et al. 2019). A plausible hypothesis on the origins of perceptual pitch-brightness interactions would be that listeners internalize the association of these dimensions of sound and consecutively apply the corresponding heuristic to any auditory input. Such a perspective would fit with developmental data that has shown three- and seven-month-old infants to be “immune” to the interaction of F_0 and SC (Lau, Oxenham, and Werner 2021).

“Timbral” and “Orchestral”: Two Distinct Modes of Brightness?

We might be tempted to conclude that brightness can be singularly explained by means of quantitative physical properties and therefore rendered intelligible via perceptual-semantic mechanisms alone. While scientific accounts of timbral brightness (often derived from isolated acoustic or synthetic stimuli) address necessary facets of auditory perception and raise crucial questions regarding its multidimensionality, they lack sufficiency in the context of orchestral music, at least to date. Since perceptual experiments rely primarily on artificial stimuli and rarely employ orchestral music with all of its complexity, the following section seeks to identify how experiences of brightness might arise in orchestral contexts. If the act of listening to multi-timbral orchestral music can involve experiences of brightness, such experiences likely result from an aggregated, multifaceted, and temporally extended encounter with orchestral sonority. We should therefore assume a wide universe of potentialities for orchestrating brightness. Likewise, we should assume a cooperative role for perceptual-semantic accounts in any explanation of ecologically valid experiences of orchestral brightness. Determining how psychoacoustical accounts of timbral brightness might come to bear on both listening and the act of orchestration requires that we first consider the phenomenon of orchestral brightness.

Varieties of Orchestral Brightness

The mystery posed by brightness only compounds when we move from the controlled conditions of timbre perception studies to the composed and performed *in situ* experience of orchestral music—seated in a concert hall, at the cinema, at the theatre, or listening attentively by other mediated means. Composers and performers manipulate brightness in the co-realization of an orchestral score (to be sure, recording engineers and even acoustic environments also participate). That brightness serves as a prevalent but indeterminate term of art for orchestrators is evidenced by the extant orchestration treatises and manuals (Wallmark 2019), where instances of instrumental brightness are itemized and exemplified,

if only in a generic manner. At a fundamental level of sonic organization, one might well argue that the regular back-and-forth fluctuations of sonic brightness in any given orchestral work or performance operate as an innate structure in that music's unfolding. Here the symphonies of Anton Bruckner and the operas of Richard Wagner stand out as emblematic of the constant and often heightened interplay between sensations of darkness and brightness as a dialectic of opposing forces (Scott 2004, Tarasti 2001) where vacillation, accidental or otherwise, takes on a contrastive role in orchestral ebb and flow.

Encultured listeners might make the bold but reasonable suggestion that even whole movements or entire works can exhibit a macro-level quality of brightness, where the overall ascription of "bright" or "dark" applies to a particular bounded duration relative to others. This form of ascription occurs when we think that the work or movement (as a whole) displays a general yet durable character of brightness or darkness relative to most of the works or movements with which a listener is familiar. Such large-scale characterizations sometimes reflect the specific instrumental configuration privileged at the outset of an orchestration, for example in Alfred Schnittke's *Concerto for Viola and Orchestra*, where the tragicomical and wholesale omission of violins alters our habitual inter-opus experience of the orchestra, skewing overall impressions toward a darkness that is attributable in part to absence. Brightness too extends as an aura that persists across entire works or movements. Take, for example, Tchaikovsky's *Serenade in C Major for String Orchestra*, where the composer maintains a generalizable sonority—understood here in its simplest sense as the interplay between registral spacing and instrumental timbre—whose quality persists across change, thereby suffusing a joyful fullness and brightness despite the small size of the ensemble and its relative timbral homogeneity. The compound sense of brightness that pervades the first movement of Beethoven's *Piano Concerto No. 4* could even be said to result at once from (I) the privileged sonic positioning of the piano, (II) the various sweeping registral emphases and attendant sonorous configurations that pass by in the ebb and flow of the music, as well as (III) the opening movement's relation to the subsequent and much darker second movement.

Yet, beyond functioning as a descriptor for this or that instrument orchestrated or played in such and such a way (I), or as a momentary ascription to characterize a fleeting passage of multi-timbral orchestral sound vis-à-vis an immediate predecessor (II), or even as an abiding inter- or intra-opus quality (III), composers have for centuries organized orchestral brightness into directional formal units when they undertake the seemingly impossible task of depicting luminosity itself in music (IV). Table 12.1 proposes a preliminary typology of orchestral brightness based on these four varieties. Whether or not depictions of light function merely as metaphors remains outside the scope of the present chapter. However, irrespective of their yet-to-be-determined status as somehow veridical or otherwise figurative, depictions of light arrive in listening experience as both highly affective and intricately cognitive, and their sonic constituents are certainly crafted with, at minimum, depictive intent. Importantly, they operate temporally as organized goal-directed contours. Since depictions of light in music are largely undocumented and undertheorized, the following section focuses on progressive-directional brightness (IV) and its manifestation as orchestrated formal contours.

Brightness and Contour: The Sunlight Topic and the Orchestral Crescendo

In music theory and music psychology, the term "contour" typically refers to sequential relationships between a series of adjacent changes in pitch and is therefore commonly

TABLE 12.1 A preliminary typology of orchestral brightness.

Type	Object of Brightness	Characteristics
I Timbral- indexical	Instrumental timbre (includes identifying a single instrumental timbre within an otherwise complex multi-timbral texture).	An immediate attribution where the sense of brightness is directly source-bonded with instrumental identity.
II Dialectical	Gestures relative to other gestures previously heard in the work.	Sensations and ascriptions of brightness in a given moment are understood relative to previous moments in the ebb and flow of the music.
III Dialogical	Whole movements or works.	Inter- and intra-work relations of brightness. A generalized and static ascription of brightness characteristic of a bounded duration relative to other works with which the listener is familiar.
IV Progressive- directional	A formal unit or process that engenders a generalized sense of progressive directional change in brightening or darkening.	An ongoing process is attended to whose immediate present is associated with the bright/dark trajectory of its past. In retrospect, the process is understood as directional and contoured.

conceived of as melodic in nature. However, other less considered parameters of musical structuring and facets of listening are amenable to a contour-based conception, including larger-scale and non-adjacent patterns and shapings. Polansky and Bassein (1992) assert that contour “may be applied to any parameter of music at any hierarchical level” (259) and moreover that in experimental psychology “the use of a linear definition of contour substantially limits the possible complexity of stimuli” (260). Addressing the music of composers such as Varèse, Xenakis, and Ligeti, Morris (1993) proposes that in post-tonal music “contour has been generalized beyond melody and may play an important structural role in a specific composition or repertoire” (205). Echoing the Gestalt psychologists, Friedmann (1985) claims that in twentieth-century music, contour takes on an increasingly significant role for listeners, that the “perception of contour is more general than perception of pitch,” and furthermore that in comparison to a pitch-specific understanding, “the contour of a musical unit may be . . . most easily grasped *and related to other musical features*” (224, italics added). Godøy (2019) suggests not only that contour can indeed designate melodic, harmonic, rhythmic, textural, dynamic, and expressive parameters of musical experience, but that a shaped cognition of music differs in quality at several timescales, what he terms the micro, meso, and macro levels, where the macro timescale “could be important for musical shape cognition . . . on a narrative or dramaturgical level” (245).

Elaine Sisman (2013) first proposed the orchestral sunrise as a common subject of musical depiction in operatic and symphonic music of the eighteenth century, arguing that “passages that might be termed ‘sunrise music,’ whether or not they appear in an explicit solar context, usually feature rising-and-growing gestures that are easily perceived as ‘representing’

or ‘characterizing’ the rising motion of the sun, or the emergence of light more generally” (9). The orchestral sunrise likely migrated from the intermedial opera stage, where orchestral crescendi featured prominently in overtures. Together with other commentators (Spitzer and Zaslaw 2004; Goodchild 2016), Sisman locates the dual character of the orchestral crescendo in music that features a slowly rising register while being concurrently intensified by the progressive addition of instruments to the overall texture. The sunrise topic can therefore be thought of as a narrative or dramaturgical form of the orchestral crescendo that involves the coordinated parametric intensification of pitch height, registral energy, ambitus, loudness, and instrumental participation—what Goodchild, Wild, and McAdams (2019) term “gradual addition” in orchestration.

Pointing to the continuation of the topic in nineteenth- and twentieth-century tonal music, Sisman (2014) suggests Wagner’s Prelude to *Das Rheingold* and Ravel’s *Daphnis et Chloé* as later developments of both the orchestral crescendo and the sunrise topic. Although never explicitly conceived of as a large-scale *contour* (e.g., Goodchild, Wild, and McAdams 2019, where contour refers only to pitch-specific ambitus as the movement of outer voices within a texture), the relative prominence of the orchestrated crescendo is clearly framed and exemplified as a continuous and explicitly unidirectional linear phenomenon. However, as Touizar (2019) points out, while expanding the topical universe to include the darkening orchestral decrescendo and its correlate depiction of sunset, luminous contours can also operate as seemingly non-linear compound forms in tonal music. These forms periodically interrupt their own teleological progression, turning back upon themselves by dissipating sonic energy (pitch height, register, ambitus, loudness, instrumental participation, etc.) after climaxes only to resume their upward and outward (or in the case of the sunset topic, downward and recessionary) trajectories once again, prior to achieving their terminal maximal or minimal degree of orchestrated brightness.

This progressive expansion-contraction pattern of orchestral brightness engenders an aggregated formal contour that, despite its changing directionality and intensity, can be understood in retrospect as a directional unity and generalized in terms of brightening or darkening contours (Touizar, Mendoza Garay, and Thompson 2023; Touizar 2021).

The Curious Case of Schoenberg’s *Farben*: *Ein Sommermorgen am See*, op. 16, No. 3

Depictions of luminosity in orchestral music continue beyond the common-practice era and persist to the present day. The third movement of Schoenberg’s Five Pieces for Orchestra (composed 1909/revised 1949), whose scenic title translates as *Colors: A Summer Morning by the Lake*, can be seen as pivotal in this regard and typifies the evolving and sometimes radical structural and orchestrational innovations later employed by post-tonal composers. The first section of *Farben* (Figure 12.2) offers a cogent example to briefly illustrate how Schoenberg’s novel approach to composition and orchestration throughout the movement can be seen to reorient the first two varieties of orchestral brightness outlined above, *timbral-indexical* and *dialectical*.⁷

⁷ Schoenberg’s approach to composition and orchestration in *Farben* can also be understood to reorient the other two categories, dialogical and generalized-directional. However, unpacking these developments requires an extended discussion that will need to take place in another forum.

FIGURE 12.2 Arnold Schoenberg, *Farben* (op. 16, No. 3), mm. 1–11. Dashed boxes indicate downbeat chords, and solid boxes indicate third-beat chords.

We can understand timbral-indexical brightness as an ascription whereby the sensation and identification of brightness are fused with and therefore inseparable from the particular timbral characteristics and identity of the source of the sound—the specific instrument from which it emanates. That is, when the source is familiar and distinct, any sense of brightness is ascribed to the source itself. When multiple concurrent timbres blend such that their sources disappear from perceptual prominence, ascriptions of brightness do not anymore bond to physical sources, but to the resulting sonorities themselves.⁸ Schoenberg weakens the indexical source-bondedness of individual instruments by both depressing general dynamics and partly masking important onset information that helps to engender instrumental identity. By methodically attenuating simultaneous onsets and in turn privileging the relative smoothness of post-onset acoustic envelopes, Schoenberg helps to facilitate timbral blending as a structural feature of the orchestration where it might otherwise be difficult and imperfect.⁹ Schoenberg achieves partial masking by overlapping the end of one sonority with the onset of the subsequent one, providing limited acoustic cover to onsets and engendering a

⁸ The use of sonority here is related to but distinct from “emergent blend” as defined by McAdams, Goodchild, and Soden (2022). Sonority is a multifaceted term. Here it encapsulates not only the blending of constituent timbres into a larger complex, but also the specific registral spacing of harmonic content. Additional adjacent perspectives on the notion of orchestral sonority can be found in Whittall (this volume), Rosner (this volume), and Touizrar (this volume). See also the Editor’s Introduction in this volume. For important foundational work, see also Hasegawa (2018).

⁹ For important foundational work on timbral blending in orchestration, see Sandell (1995). For a comprehensive examination of blend as a condition for various grouping effects in the orchestral literature, see also McAdams, Goodchild, and Soden (2022).

fluid continuity from one sonority to the next. The resulting masking of instrumental attacks and textural lack of prominence for any one instrumental timbre systematically impairs indexical brightness, shifting the source of brightness away from individual instruments, and therefore away from listeners' familiar source-cause categories, at least for the harmonic-textural layers throughout the movement that feature blended sonorities.¹⁰ Indeed, lacking the normative melodic primacy common to most tonal music, brightness here is no longer bound together with pitch progression or harmonic syntax. This general inversion runs contrary to the traditional act whereby an orchestrator "gives a line" to this or that instrument. For if brightness exceeds a specific instrument's or instrumental family's particular and distinct sound quality, then it must be understood to shift away from association with instrumental identity, toward the multi-timbral and multi-sourced complex of sonority, for which the formation of source-cause categories is likely extremely difficult. From a discernable and familiar singularity to a provisionally unified, vague, and somewhat unfamiliar multiplicity. At the same time, the masking and strong blending that results from attenuating onsets also help to downplay pitch identification. This raises the question of pitch-brightness interaction effects demonstrated in the experimental literature and points toward potentially fruitful future work to determine if interaction effects can be measured using complex, ecologically valid stimuli like *Farben*.

The experience of brightness in *Farben* emerges in large part from sonorities and their relations relative to one another as they unfold within listening experience, as a dialectic. Of course, individual timbres contribute to the overall sense of brightness within a given sonority, yet their identities are at best minimally perceptible and therefore not important as such.¹¹ Whereas the loss of onset information facilitates the large-scale blend, and therefore the aggregation of timbre into sonority, harmonic and orchestrational stability in the form of repetition, together with the rhythmic regularity of the onset pattern, facilitate immediate comparison between sonorities from moment to moment in an echo-like fashion. In one way of hearing, the consistency of sonorous vacillation in the opening phrase allows for a binary dialectic of brightness to be established. Under such a hearing, the first constituent of the dialectic (mm. 1–9; downbeat chords orchestrated with flutes 1 and 2, clarinet 2, bassoon 2) sounds both louder and darker than its echo in the second (mm. 1–9; third-beat chords orchestrated with English horn, trumpet 2 muted, bassoon 1, horn 2 muted), which while sounding slightly softer also presents as brighter. One possible explanation for the increased sense of brightness in the second chord relative to the first lies in the spectral profiles of the two groups of instruments, which progress from less complex (first chord) to more complex (second chord). The English horn plays in a relatively high register and replaces flute 1 playing in its darker low (and softer) register. Similarly, the use of muted trumpet, bassoon, and muted horn in the second chord to replace flute, clarinet, and bassoon, respectively, adds a small amount of higher-frequency energy to the second chord (see Figure 12.3). It is important to note that while indexicality qua instrumental identity is largely skewed, an intimate familiarity with the specific quality of instrumental timbre is required to craft such a refined

¹⁰ Schoenberg does foreground timbral-indexical brightness to various degrees in a series of brief and pointillistic spurts throughout the movement, for example with the celesta, harp, and piccolo in measures 20–21, and in the bass clarinet at measure 7, which serves to emphasize a lack of brightness. Importantly, these sonic flurries mostly exceed the general tessitura of the rest of the music, withholding the upper and lower bounds of the orchestra's range for brief punctuation.

¹¹ For an innovative approach to measuring the individual contributions to brightness within a sonority or textural configuration, see Spencer (2022).

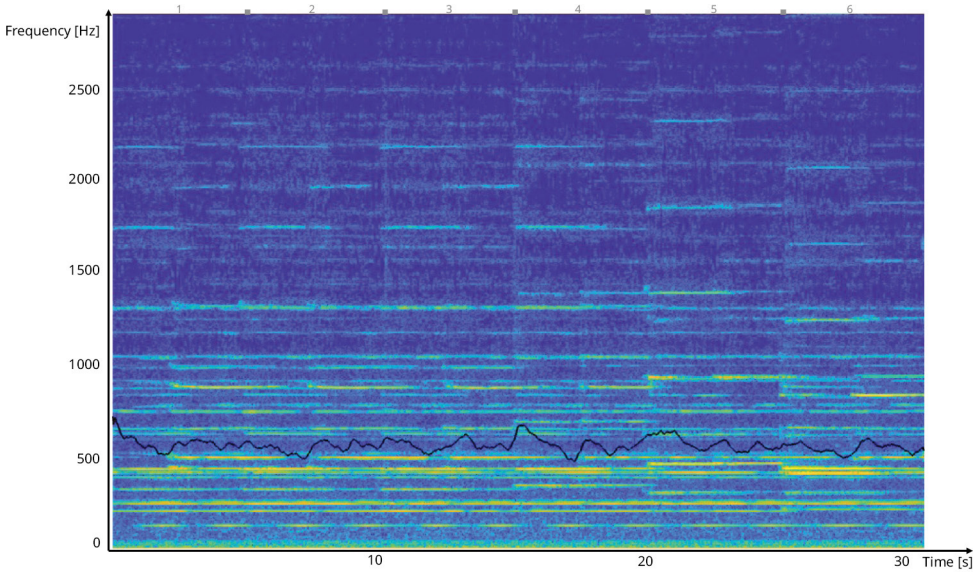


FIGURE 12.3 Spectrogram plot of *Farben* mm. 1–6 with overlaid spectral centroid contour.

and unique orchestrational dialectic—the orchestrator must possess profound indexical insight and contextual intuition concerning individual instruments in order to imagine, exploit, and blend timbre to such a nuanced degree. That is, timbral-indexical knowledge and know-how facilitate both the higher-order construction of sonority and the dialectical control of brightness.

Hearing Brightness at the Crossroads

We return, then, to the beginning of Strauss’s *Also sprach Zarathustra* (Sunrise) and the main questions that were raised at the start of this chapter: (i) how timbre and orchestration each contributes to the phenomenon of sonic brightness, and (ii) where to locate brightness at the crossroads of perceptual studies and orchestration theory.¹² Is brightness to be located in the spectra of momentary sounds, specifically in their spectral centroid, as the experimental timbre research reviewed here consistently suggests? This notion of *localizable* brightness is important and operates in both isolated instances of timbre as well as in the large-scale aggregation of timbre into orchestral sonority. Figure 12.4 shows a spectrogram of Strauss’s Sunrise.¹³ The spectra for the melodic motion and chordal complexes are clearly delineated, with yellow-green regions defining strong signals from the fundamental and overtones of

¹² Here, we reference a paper titled “Hearing Timbre at the Crossroads” by Landon Morrison (2022). The duality of understanding brightness as a perceptual-scientific fact and as orchestral-creative practice reflects the entanglement of timbre with “a vast range of epistemic instruments, cultural practices, and listening techniques” (328; cf. Saitis et al. 2024, 2025).

¹³ Computed with Matlab’s standard “spectrogram.m” function using a 186ms window length (Hamming window) with 23ms hop size. Based on the 2012 (released 2013) Deutsche Grammophon live recording performed by the Berliner Philharmoniker and conducted by Gustavo Dudamel (Catalogue Number: 4791041).

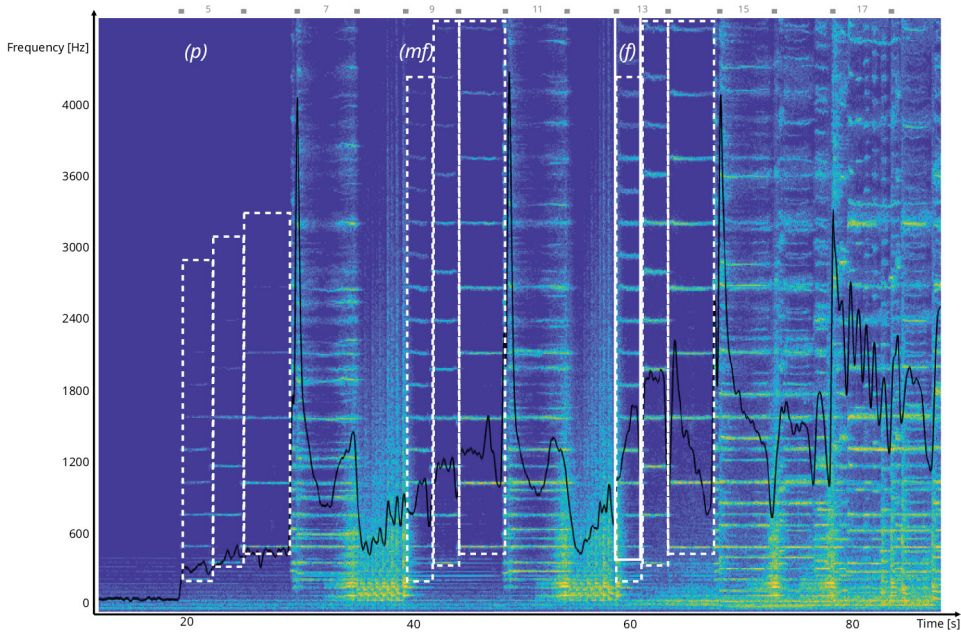


FIGURE 12.4 Spectrogram plot of “Sonnenaufgang” mm.1–18 with overlaid spectral centroid contour.

each note. The temporal evolution of the spectral centroid is overlaid in black.¹⁴ There is an evident layering effect as Strauss orchestrates a build-up of higher-frequency energy from the lower frequencies to the full spectrum of the orchestra through continually reinforcing and expanding overtones emanating from the notes of the C-G-C motif (played in the first iteration by two trumpets, and in subsequent iterations by four trumpets). For example, we can follow the initially weak G6 at 1568 Hz as it gradually gets more pronounced, first by becoming 4th partial to the subsequent G4 and 3rd partial to the following C5, then by itself becoming the fundamental of new notes played by new instruments in the chordal complexes (ditto for the G7 at 3136 Hz).

Yet hearing brightness in Strauss’s Sunrise is also a *distributed* process—a sense of *brightening*—that both resists and transcends any definitive localization, being built up over time and repetition within experience. As the music evolves through the terraced dynamics of the C-G-C motif (*p-mf-f*) and the re-voicing of the punctuated chordal complex at each iteration (see Figure 12.1), the listener’s experience of orchestral brightness recalibrates (see Figure 12.4) in response to the changing orchestral sonority and energy. Brightening, as a formal process in music composition, orchestration, and listening, is therefore a time-bound interpretation—the experiential aggregation of many local instances of brightness into a generalized contour. Composers and orchestrators craft moments of brightness and organize them into an intelligible progression that allows the listener to “trace” the evolution of brightness not as a uniform line that simply increases steadily in brightness, but as a dynamic, evolving, sometimes retreating contour capable of discrete states of brightness where the re-articulation of progressive increase engenders the unified sense of brightening.

¹⁴ Computed according to standard formula directly from the magnitude spectrogram with linear amplitude and frequency units, but only considering contributions when these are above -60 dB full scale.

Importantly, Figure 12.4 shows that the spectral centroid diverges from tracking this lived experience of brightness, since it obliterates the perceived brightness of individual auditory streams under important orchestral gestures and changes to texture, such as registral expansion and contrary motion at distant registers (from 0:80 on). While spectral centroid might work well as a measure of brightness for single sounds, it works less well for compound orchestral textures such as the one Strauss creates where the very powerful low register sounds pull down the centroid despite the presence of a very prominent and bright high chord.

More broadly, there is a divergence of our scientific understanding of brightness as a function of sound wave properties and auditory perception on the one hand, and brightness as a facet of orchestral listening experiences on the other. And yet, as this chapter demonstrates, there is no doubt that timbral and orchestral forms of brightness are related and interact. The perception of changes in the frequency content of sounds over time, its adaptive nature, and the co-evolution of timbral brightness with pitch and dynamics all play roles in shaping the listener's experience of orchestral brightness. It is precisely this experience—where brightness as localizable percept shifts from being source-bonded with a particular instrument to becoming a quality of a larger-order compound sonority—that is so difficult to capture, isolate, and account for in perceptual experiments, hence the need for further multidisciplinary research between theorists and perceptual scientists. Rather than looking for brightness in one or the other form, then, future research should aim to reconcile the different approaches, instigating productive dialogue that could lead to cross-fertilization in terms of methodologies and epistemologies. Moreover, novel cooperative methodologies for future studies into ecologically valid paradigms that incorporate psychophysical principles and findings into theories and analyses of composition and orchestration need to be developed to better understand how the perception of timbral brightness comes to bear on orchestral music, and vice versa.

Bibliography

- Allen, Emily J., and Andrew J. Oxenham. 2014. "Symmetric Interactions and Interference Between Pitch and Timbre." *The Journal of the Acoustical Society of America* 135 (3): 1371–1379. <https://doi.org/10.1121/1.4863269>.
- Arieh, Yoav, and Lawrence E. Marks. 2008. "Cross-Modal Interaction Between Vision and Hearing: A Speed–Accuracy Analysis." *Perception & Psychophysics* 70 (3): 412–421. <https://doi.org/10.3758/PP.70.3.412>.
- Barker, Andrew. 1990. *Greek Musical Writings: Volume 2, Harmonic and Acoustic Theory*. Cambridge: Cambridge University Press.
- Bell, Robert. 2015. "PAL: The Percussive Audio Lexicon." PhD diss., Swinburne University of Technology.
- Boring, Edwin Garrigues, and S. S. Stevens. 1936. "The Nature of Tonal Brightness." *Proceedings of the National Academy of Sciences* 22 (8): 514–521. <https://doi.org/10.1073/pnas.22.8.514>.
- Brent, William. 2010. "Physical and Perceptual Aspects of Percussive Timbre." PhD diss., University of California, San Diego.
- Caclin, Anne, Stephen McAdams, Bennett K. Smith, and Suzanne Winsberg. 2005. "Acoustic Correlates of Timbre Space Dimensions: A Confirmatory Study Using Synthetic Tones." *The Journal of the Acoustical Society of America* 118 (1): 471–482. <https://doi.org/10.1121/1.1929229>.
- Caetano, Marcelo, Charalampos Saitis, and Kai Siedenburg. 2019. "Audio Content Descriptors of Timbre." In *Timbre: Acoustics, Perception, and Cognition*, edited by Kai Siedenburg, Charalampos Saitis, Stephen McAdams, Arthur N. Popper, and Richard R. Fay, 297–333. Cham: Springer. https://doi.org/10.1007/978-3-030-14832-4_11.

- Chambers, Claire, Sahar Akram, Vincent Adam, Claire Pelofi, Maneesh Sahani, Shihab Shamma, and Daniel Pressnitzer. 2017. "Prior Context in Audition Informs Binding and Shapes Simple Features." *Nature Communications* 8: 15027. <https://doi.org/10.1038/ncomms15027>.
- Cousineau, Marion, Samuele Carcagno, Laurent Demany, and Daniel Pressnitzer. 2014. "What Is a Melody? On the Relationship Between Pitch and Brightness of Timbre." *Frontiers in Systems Neuroscience* 7: 127. <https://doi.org/10.3389/fnsys.2013.00127>.
- Dau, Torsten, Dirk Püschel, and Armin Kohlrausch. 1996. "A Quantitative Model of the 'Effective' Signal Processing in the Auditory System. I. Model Structure." *The Journal of the Acoustical Society of America* 99 (6): 3615–3622. <https://doi.org/10.1121/1.414959>.
- Dictionnaire de l'Académie française*. 1740. ed. 2 vols., Paris: Jean-Baptiste Coignard.
- Dolan, Emily I. 2013. *The Orchestral Revolution: Haydn and the Technologies of Timbre*. Cambridge: Cambridge University Press.
- Drouzas, Christos, and Charalampos Saitis. 2020. "Verbal Description of Musical Brightness." In *Proceedings of the 2nd International Conference on Timbre*, edited by Asterios Zacharakis, Charalampos Saitis, and Kai Siedenburg, 42–35. Thessaloniki: The School of Music Studies Aristotle University of Thessaloniki.
- Edwards, Paul N., Matthew S. Mayernik, Archer L. Batcheller, Geoffrey C. Bowker, and Christine L. Borgman. 2011. "Science Friction: Data, Metadata, and Collaboration." *Social Studies of Science* 41 (5): 667–690. <https://doi.org/10.1177/0306312711413314>.
- Faure, Anne, Stephen McAdams, and Valéry Nosulenko. 1996. "Verbal Correlates of Perceptual Dimensions of Timbre." In *Proceedings of the 4th International Conference on Music Perception and Cognition*, edited by Bruce Pennycook and Eugenia Costa-Giomi.
- Friedmann, M. L. 1985. "A Methodology for the Discussion of Contour: Its Application to Schoenberg's Music." *Journal of Music Theory* 29 (2): 223–248. <https://doi.org/10.2307/843614>.
- Garner, Wendell R., and Gary L. Felfoldy. 1970. "Integrality of Stimulus Dimensions in Various Types of Information Processing." *Cognitive Psychology* 1 (3): 225–241. [https://doi.org/10.1016/0010-0285\(70\)90016-2](https://doi.org/10.1016/0010-0285(70)90016-2).
- Godøy, Rolf. 2019. "Musical Shape Cognition." In *The Oxford Handbook of Sound and Imagination*, edited by Mark Grimshaw-Aagaard, Mads Walther-Hansen, and Martin Knakkergaard, 237–258. Oxford: Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780190460242.013.10>.
- Goodchild, Meghan. 2016. "Orchestral Gestures: Music-theoretical Perspectives and Emotional Responses." PhD diss., McGill University.
- Goodchild, Meghan, Jonathan Wild, and Stephen McAdams. 2019. "Exploring Emotional Responses to Orchestral Gestures." *Musicae Scientiae* 23 (1): 25–49. <https://doi.org/10.1177/1029864917704033>.
- Gottschalk, H. B. 1968. "The De Audibilibus and Peripatetic Acoustics." *Hermes* 96 (3): 435–460. <https://www.jstor.org/stable/4475532>.
- Grey, John. M. 1977. "Multidimensional Perceptual Scaling of Musical Timbres." *Journal of the Acoustical Society of America* 61 (5): 1270–1277. <https://doi.org/10.1121/1.381428>.
- Hasegawa, Robert. 2018. "Timbre as Harmony—Harmony as Timbre." In *The Oxford Handbook of Timbre*, edited by Emily I. Dolan and Alexander Rehding, 525–551. Oxford: Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780190637224.013.11>.
- Hayes, Ben, Charalampos Saitis, and György Fazekas. 2022. "Disembodied Timbres: A Study on Semantically Prompted FM Synthesis." *Journal of the Audio Engineering Society* 70 (5): 373–391. <https://doi.org/10.17743/jaes.2022.0006>.
- Holt, Lori L. 2005. "Temporally Nonadjacent Nonlinguistic Sounds Affect Speech Categorization." *Psychological Science* 16 (4): 305–312. <https://doi.org/10.1111/j.0956-7976.2005.01532.x>.
- Jacobsen, Simon, and Kai Siedenburg. 2024. "Exploring the Relation Between Fundamental Frequency and Spectral Envelope in the Perception of Musical Instrument Sounds." *Acta Acustica* 8: 48. <https://doi.org/10.1051/aacus/2024038>.
- Jacoby, Nori, Eduardo A. Undurraga, Malinda J. McPherson, Joaquín Valdés, Tomás Ossandón, and Josh H. McDermott. 2019. "Universal and Non-Universal Features of Musical Pitch Perception Revealed by Singing." *Current Biology* 29 (19): 3229–3243. <https://doi.org/10.1016/j.cub.2019.08.020>.

- Kendall, Roger A., and Edward C. Carterette. 1993. "Verbal Attributes of Simultaneous Wind Instrument Timbres: I. Von Bismarck's Adjectives." *Music Perception* 10 (4): 445–467. <https://doi.org/10.2307/40285583>.
- Lau, Bonnie K., Andrew J. Oxenham, and Lynne A. Werner. 2021. "Infant Pitch and Timbre Discrimination in the Presence of Variation in the Other Dimension." *Journal of the Association for Research in Otolaryngology* 22 (6): 693–702. <https://doi.org/10.1007/s10162-021-00807-1>.
- Loughridge, Deirdre. 2018. "Timbre Before Timbre: Listening to the Effects of Organ Stops, Violin Mutes, and Piano Pedals ca. 1650–1800." In *The Oxford Handbook of Timbre*, edited by Emily I. Dolan and Alexander Rehding, 268–290. Oxford: Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780190637224.013.16>.
- Marozeau, Jeremy, and Alain de Cheveigné. 2007. "The Effect of Fundamental Frequency on the Brightness Dimension of Timbre." *The Journal of the Acoustical Society of America* 121 (1): 383–387. <https://doi.org/10.1121/1.2384910>.
- Marozeau, Jeremy, Alain de Cheveigné, Stephen McAdams, and Suzanne Winsberg. 2003. "The Dependency of Timbre on Fundamental Frequency." *The Journal of the Acoustical Society of America* 114 (5): 2946–2957. <https://doi.org/10.1121/1.1618239>.
- McAdams, Stephen. 2019. "The Perceptual Representation of Timbre." In *Timbre: Acoustics, Perception, and Cognition*, edited by Kai Siedenburg, Charalampos Saitis, Stephen McAdams, Arthur N. Popper, and Richard R. Fay, 23–57. Cham: Springer. https://doi.org/10.1007/978-3-030-14832-4_2.
- McAdams, Stephen, Meghan Goodchild, and Kit Soden. 2022. "A Taxonomy of Orchestral Grouping Effects Derived from Principles of Auditory Perception." *Music Theory Online* 28 (3). <https://doi.org/10.30535/mto.28.3.6>.
- McAdams, Stephen, Suzanne Winsberg, Sophie Donnadiu, Geert De Soete, and Jochen Krimphoff. 1995. "Perceptual Scaling of Synthesized Musical Timbres: Common Dimensions, Specificities, and Latent Subject Classes." *Psychological Research* 58 (3): 177–192. <https://doi.org/10.1007/BF00419633>.
- McDermott, Josh H., Andriana J. Lehr, and Andrew J. Oxenham. 2008. "Is Relative Pitch Specific to Pitch?" *Psychological Science* 19 (12): 1263–1271. <https://doi.org/10.1111/j.1467-9280.2008.02235.x>.
- McDermott, Josh H., Alan F. Schultz, Eduardo A. Undurraga, and Ricardo A. Godøy. 2016. "Indifference to Dissonance in Native Amazonians Reveals Cultural Variation in Music Perception." *Nature* 535: 547–550. <https://doi.org/10.1038/nature18635>.
- Melara, Robert D., and Lawrence E. Marks. 1990. "Interaction Among Auditory Dimensions: Timbre, Pitch, and Loudness." *Perception & Psychophysics* 48 (2): 169–178. <https://doi.org/10.3758/BF03207084>.
- Miller, James R., and Edward C. Carterette. 1975. "Perceptual Space for Musical Structures." *The Journal of the Acoustical Society of America* 58 (3): 711–720. <https://doi.org/10.1121/1.380719>.
- Morris, Robert D. 1993. "New Directions in the Theory and Analysis of Musical Contour." *Music Theory Spectrum* 15 (2): 205–228. <https://doi.org/10.2307/745814>.
- Morrison, Landon. 2022. "Hearing Timbre at the Crossroads." *Kalfou* 9 (2): 328–336. <https://doi.org/10.15367/kf.v9i2.632>.
- Osgood, Charles E. 1952. "The Nature and Measurement of Meaning." *Psychological Bulletin* 49 (3): 197–237. <https://doi.org/10.1037/h0055737>.
- Parise, Cesare V., Katharina Knorre, and Marc O. Ernst. 2014. "Natural Auditory Scene Statistics Shapes Human Spatial Hearing." *Proceedings of the National Academy of Sciences* 111 (16): 6104–6108. <https://doi.org/10.1073/pnas.1322705111>.
- Patterson, Roy D., Robert Milroy, and Michael Allerhand. 1993. "What Is the Octave of a Harmonically Rich Note?" *Contemporary Music Review* 9 (1–2): 69–81. <https://doi.org/10.1080/07494469300640351>.
- Pitt, Mark A. 1994. "Perception of Pitch and Timbre by Musically Trained and Untrained Listeners." *Journal of Experimental Psychology: Human Perception and Performance* 20 (5): 976–986. <http://dx.doi.org/10.1037/0096-1523.20.5.976>.

- Pitteri, Marco, Mauro Marchetti, Konstantinos Priftis, and Massimo Grassi. 2017. "Naturally Together: Pitch-Height and Brightness as Coupled Factors for Eliciting the SMARC Effect in Non-Musicians." *Psychological Research* 81 (1): 243–254. <https://doi.org/10.1007/s00426-015-0713-6>.
- Polansky, Larry, and Richard Bassein. 1992. "Possible and Impossible Melody: Some Formal Aspects of Contour." *Journal of Music Theory* 36 (2): 259–284. <https://doi.org/10.2307/843933>.
- Pratt, Carroll C. 1930. "The Spatial Character of High and Low Tones." *Journal of Experimental Psychology* 13 (3): 278. <https://doi.org/10.1037/h0072651>.
- Reymore, Lindsey, Jason Noble, Charalampos Saitis, Caroline Traube, and Zachary Wallmark. 2023. "Timbre Semantic Associations Vary Both Between and Within Instruments: An Empirical Study Incorporating Register and Pitch Height." *Music Perception* 40 (3): 253–274. <https://doi.org/10.1525/mp.2023.40.3.253>.
- Rosi, Victor, Pablo Arias, Olivier Houix, Nicolas Misdariis, and Patrick Susini. 2023. "Shared Mental Representations Underlie Metaphorical Sound Concepts." *Scientific Reports* 13: 5180. <https://doi.org/10.1038/s41598-023-32214-2>.
- Rosi, Victor, Olivier Houix, Nicolas Misdariis, and Patrick Susini. 2022. "Investigating the Shared Meaning of Metaphorical Sound Attributes: Bright, Warm, Round, and Rough." *Music Perception* 39 (5): 468–483. <https://doi.org/10.1525/mp.2022.39.5.468>.
- Rousseau, Jean-Jacques. 1765a. "Son." In *Encyclopédie: ou Dictionnaire raisonné des sciences, des arts et des métiers*, volume 15, edited by D. Diderot and J. d'Alembert. Paris.
- Rousseau, Jean-Jacques. 1765b. "Tymbre." In *Encyclopédie: ou Dictionnaire raisonné des sciences, des arts et des métiers*, volume 15, edited by D. Diderot and J. d'Alembert. Paris.
- Rusconi, Elena, Bonnie Kwan, Bruno L. Giordano, Carlo Umiltà, and Brian Butterworth. 2006. "Spatial Representation of Pitch Height: The SMARC Effect." *Cognition* 99 (2): 113–129. <https://doi.org/10.1016/j.cognition.2005.01.004>.
- Saitis, Charalampos, Bleiz M. Del Sette, Jordie Shier, Haokun Tian, Shuoyang Zheng, Sophie Skach, et al. 2024. "Timbre Tools: Ethnographic Perspectives on Timbre and Sonic Cultures in Hackathon Designs." In *Proceedings of the 19th International Audio Mostly Conference: Explorations in Sonic Cultures*, 229–244. <https://doi.org/10.1145/3678299.3678322>.
- Saitis, Charalampos, Courtney N. Reed, Ashley Laurent Noel-Hirst, Giacomo Lepri, and Andrew McPherson. 2025. "(De)Constructing Timbre at NIME: Reflecting on Technology and Aesthetic Entanglements in Instrument Design." In *Proceedings of the International Conference on New Interfaces for Musical Expression, 197–206*. <https://doi.org/10.5281/zenodo.15698835>
- Saitis, Charalampos, and Kai Siedenburg. 2020. "Brightness Perception for Musical Instrument Sounds: Relation to Timbre Dissimilarity and Source-Cause Categories." *The Journal of the Acoustical Society of America* 148 (4): 2256–2266. <https://doi.org/10.1121/10.0002275>.
- Saitis, Charalampos, Kai Siedenburg, Paul Schuladen, and Christoph Reuter. 2019. "The Role of Attack Transients in Timbral Brightness Perception." In *Proceedings of the 23rd International Congress on Acoustics*, edited by Martin Ochmann, Michael Vorländer, and Janina Fels, 5506. Berlin: Deutsche Gesellschaft für Akustik.
- Saitis, Charalampos, and Zachary Wallmark. 2024. "Timbral Brightness Perception Investigated through Multimodal Interference." *Attention, Perception, & Psychophysics* 86: 1835–1845. <https://doi.org/10.3758/s13414-024-02934-2>.
- Saitis, Charalampos, and Stefan Weinzierl. 2019. "The Semantics of Timbre." In *Timbre: Acoustics, Perception, and Cognition*, edited by Kai Siedenburg, Charalampos Saitis, Stephen McAdams, Arthur N. Popper, and Richard R. Fay. Cham: Springer. https://doi.org/10.1007/978-3-030-14832-4_5.
- Sandell, Gregory J. 1995. "Roles for Spectral Centroid and Other Factors in Determining 'Blended' Instrument Pairings in Orchestration." *Music Perception* 13 (2): 209–246. <https://doi.org/10.2307/40285694>.
- Schneider, Peter, Vanessa Sluming, Neil Roberts, Michael Scherg, Rainer Goebel, Hans J. Specht, et al. 2005. "Structural and Functional Asymmetry of Lateral Heschl's Gyrus Reflects Pitch Perception Preference." *Nature Neuroscience* 8 (9): 1241–1247. <https://doi.org/10.1038/nn1530>.

- Scott, Derek. 2004. "Bruckner's Symphonies—a Reinterpretation: the Dialectic of Darkness and Light." In *The Cambridge Companion to Bruckner*, edited by John Williamson, 92–107. Cambridge: Cambridge University Press. doi:10.1017/CCOL9780521804042.009.
- Shepard, R. N. 1962. "The Analysis of Proximities: Multidimensional Scaling with an Unknown Distance Function. I." *Psychometrika* 27 (2): 125–140. <https://doi.org/10.1007/BF02289630>.
- Shepard, Roger N. 1964. "Circularity in Judgments of Relative Pitch." *The Journal of the Acoustical Society of America* 36 (12): 2346–2353. <https://doi.org/10.1121/1.1919362>.
- Siedenburg, Kai. 2018. "Timbral Shepard-Illusion Reveals Perceptual Ambiguity and Context Sensitivity of Brightness Perception." *Journal of the Acoustical Society of America* 143 (2): EL93–EL98. <https://doi.org/10.1121/1.5022983>.
- Siedenburg, Kai, Feline Malin Barg, and Henning Schepker. 2021. "Adaptive Auditory Brightness Perception." *Scientific Reports* 11 (1): 1–11. <https://doi.org/10.1038/s41598-021-00707-7>.
- Siedenburg, Kai, Jackson Graves, and Daniel Pressnitzer. 2023. "A Unitary Model of Auditory Frequency Change Perception." *PLOS Computational Biology* 19 (1): 1–30. <https://doi.org/10.1371/journal.pcbi.1010307>.
- Siedenburg, Kai, Simon Jacobsen, and Christoph Reuter. 2021. "Spectral Envelope Position and Shape in Orchestral Instrument Sounds." *The Journal of the Acoustical Society of America* 149 (6): 3715–3727. <https://doi.org/10.1121/10.0005088>.
- Siedenburg, Kai, Kiray Jones-Mollerup, and Stephen McAdams. 2016. "Acoustic and Categorical Dissimilarity of Musical Timbre: Evidence from Asymmetries Between Acoustic and Chimeric Sounds." *Frontiers in Psychology* 6: 1977. <https://doi.org/10.3389/fpsyg.2015.01977>.
- Siedenburg, Kai, and Stephen McAdams. 2018. "Short-Term Recognition of Timbre Sequences: Music Training, Pitch Variability, and Timbral Similarity." *Music Perception* 36 (1): 24–39. <https://doi.org/10.1525/mp.2018.36.1.24>.
- Sisman, Elaine. 2013. "Haydn's Solar Poetics: The Tageszeiten Symphonies and Enlightenment Knowledge." *Journal of the American Musicological Society* 66 (1): 5–102. <https://doi.org/10.1525/jams.2013.66.1.5>.
- Sisman, Elaine. 2014. "Symphonies and the Public Display of Topics." In *The Oxford Handbook of Topic Theory*, edited by Danuta Mirka, 90–117. Oxford: Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780199841578.013.004>.
- Spencer, Stephen. 2022. "Toward a Multilevel Intervallic Understanding of Brightness in Post-Tonal Music." Paper delivered at the 2022 Joint Annual Meeting of the AMS-SEM-SMT. <https://vimeo.com/771309168>.
- Spitzer, John, and Neal Zaslaw. 2004. *The Birth of the Orchestra: History of an Institution, 1650–1815*. Oxford: Oxford University Press.
- Stilp, Christian E., Joshua M. Alexander, Michael Kiefe, and Keith R. Kluender. 2010. "Auditory Color Constancy: Calibration to Reliable Spectral Properties Across Nonspeech Context and Targets." *Attention, Perception, & Psychophysics* 72 (2): 470–480. <https://doi.org/10.3758/APP.72.2.470>.
- Tarasti, Eero. 2001. "The Semiosis of Light in Music: From Synaesthetics to Narratives." *Semiotica* 2001 (136): 531–567. <https://doi.org/10.1515/semi.2001.097>.
- Touizrar, Moe. 2019. "From Ekphrasis to Apperception: The Sunrise Topic in Orchestral Music." PhD diss., McGill University.
- Touizrar, Moe. 2021. "Ekphrasis, enargeia, and the Orchestral Sunrise in Music." In *Text-Image-Music: Crossing the Borders. Intermedial Conversations on the Poetics of Verbal, Visual and Musical Texts. In Honour of Prof. Elżbieta Chrzanowska-Kluczevska*, edited by Andrzej Pawelec, Aeddan Shaw, and Grzegorz Szpila, 321–337. Berlin: Peter Lang.
- Touizrar, Moe, Juan Ignacio Mendoza Garay, and Marc R. Thompson. 2023. "Links Between Embodiment and Perceived Brightness in Orchestral Music." *Proceedings of the PAM-IE Belgrade 2022*, edited by Blanka Bogunović, Sanela Nikolić, and Dejana Mutavdžin, 17–23. Belgrade: Faculty of Music, University of Arts in Belgrade.

- Ueda, Kazuo, and Kengo Ohgushi. 1987. "Perceptual Components of Pitch: Spatial Representation Using a Multidimensional Scaling Technique." *The Journal of the Acoustical Society of America* 82 (4): 1193–1200. <https://doi.org/10.1121/1.395255>.
- Wallmark, Zachary. 2019. "A Corpus Analysis of Timbre Semantics in Orchestration Treatises." *Psychology of Music* 47 (4): 585–605. <https://doi.org/10.1177/0305735618768102>.
- Weiss, Naomi. 2018. "Tracing Timbre in Ancient Greece". In *The Oxford Handbook of Timbre*, edited by Emily I. Dolan and Alexander Rehding, 229–248. Oxford: Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780190637224.013.23>.
- Zacharakis, Asterios, Konstantinos Pasiadis, and Joshua D. Reiss. 2014. "An Interlanguage Study of Musical Timbre Semantic Dimensions and Their Acoustic Correlates." *Music Perception* 31 (4): 339–358. <https://doi.org/10.1525/mp.2014.31.4.339>.
- Zacharakis, Asterios, Konstantinos Pasiadis, and Joshua D. Reiss. 2015. "An Interlanguage Unification of Musical Timbre: Bridging Semantic, Perceptual, and Acoustic Dimensions." *Music Perception* 32 (4): 394–412. <https://doi.org/10.1525/mp.2015.32.4.394>.