Moving to the rhythm of spring
A case study of the rhythmic structure of dance*

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Abstract

The specific goal of the article is to investigate the principles governing the perception of rhythmic structure in dance and music – taken separately and together – on the basis of a case study. I take as a starting point Lerdahl and Jackendoff's (1983) conception of musical rhythm as the interaction between grouping and meter, and I examine to what extent it can apply to dance. Then, I explore how the rhythmical structures of music and dance interact in a single event. I conclude that dance and music perception largely share the same abstract system, and the differences in the properties of their structure derives from the different (visual vs. auditory) modalities in which they are perceived; their modality difference also affects the perceived structure resulting from their combination in dance-music events.
The exploration is guided by a detailed examination of the opening of Stravinsky's *Augurs of Spring* (1913) as choreographed by Nijinsky (1913), Béjart (1970) and Bausch (1975). By comparing these minimal pairs of dance-music events, I adapt the formal methodology of linguistics to other cognitive systems. The general goal of the article is to shed further light on the organizational principles of mental representations by comparing several cognitive systems in order to distinguish between general cognitive properties and modality-specific or domain-specific properties.

Keywords

Super linguistics; dance; music; rhythm; grouping; meter

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Introduction

One important aspect of the emerging field of 'Super Linguistics' consists in applying methodologies inspired by formal linguistics to diverse non-standard objects in order to investigate the organizational principles of human mental representations. In particular, the comparison of various cognitive systems should allow us to distinguish between general cognitive properties, domain-specific and modality-specific properties. Lerdahl and Jackendoff (1983) pioneered this approach for the study of music cognition: just like linguists aim at studying the human capacity for speech, they defined their goal as inquiring into the human capacity for music perception. This work inspired many studies in this vein focusing on music itself or on the comparison between music and language as cognitive systems (see Jackendoff 2009, Katz and Pesetsky 2011, Rebuschat et al. 2011, Rohrmeier 2011, Granroth-Wilding and Steedman 2014, Katz 2017, Schlenker 2017, i.a.).

The very general goal of the present article is to adopt this approach for dance and thus inquire into the human capacity for dance perception (see Charnavel 2016, 2019, Patel-Grosz et al. 2018, 2022, i.a.). This implies not only building a grammar of dance by determining its units, structure and meaning, but also comparing dance with other cognitive systems. More specifically, my aim in this paper, given that dance and music often go together, is to compare the structures of music and dance. First, I will investigate to what extent the musical structures identified by Lerdahl and Jackendoff (1983) apply to dance. Second, I will explore how music and dance structures interact in events involving both simultaneously (henceforth 'dance-music events').

Given that dance and music are largely perceived in different (visual vs. auditory) modalities, this will lead us to examine the impact of modality on cognitive systems. The similarities between sign and spoken languages, in spite of their different modality, show that language as an abstract system can be perceived in different modalities. Similarly, we will explore the hypothesis that dance and music largely share the same abstract system, thus challenging Patel's (2008: 376) claim that "sign music" does not exist.

To this end, I will specifically focus on rhythmical structure and investigate to what extent the rhythmical structure of dance can be treated as the interaction between grouping and meter preference rules as proposed by Lerdahl and Jackendoff (1983) for music. This investigation will also lead us to examine the rhythmical structure of dance-music events and specify how modality affects the way some aspects of this structure are perceived.

Concretely, the study will be based on a detailed examination of a very short passage of *the Rite of Spring* by Stravinsky (1913) as choreographed by Nijinsky (1913), Béjart (1970) and Bausch (1975); the three video excerpts can be found in the supplementary material (see section 5). Inspired by the linguistic methodology, I will thus work with minimal pairs extracted from an existing corpus of musical and dance pieces.

The outline is as follows. First, I will review Lerdahl and Jackendoff's (1983) analysis of music rhythm and apply it to our case study, namely the opening of Stravinsky's *Augurs of Spring*. Then, I will show that Lerdahl and Jackendoff's 1983 rhythmical principles of music can be adapted to dance using the choreographies under study as illustrations. Finally, I will argue, on the basis of our case study, that in a dance-music event, dance and music rhythmical structures interact to create a single rhythmical structure in a way that is partly determined by their differences in modality.

1 Applying Lerdahl and Jackendoff's 1983 rhythmical analysis to *the Augurs of Spring*

Lerdahl and Jackendoff (1983) (cf. Jackendoff and Lerdahl 2006) adopt a cognitive psychology approach to music and define the goal of music theory as a "formal description of the musical intuitions of a listener experienced in a musical idiom" (p.1). In order to specify the cognitive capacity for music, they focus on the experienced listener because listening is a more widespread activity than composing or performing, and because sufficient exposure to an idiom is required to be able to organize the music perceived in a sufficiently rich way. Lerdahl and Jackendoff's approach, which they specifically apply to Western tonal music, is based on the hypothesis that a piece of music is a mentally constructed entity, from which scores and performances are only partial representations. The main question they want to address is the following: what is the (largely unconscious) knowledge that allows the listener to organize and make coherent the surface patterns of music? In other words, music theory, under this approach, consists in building a grammar of music. Just like linguists do not focus on literary forms, but on everyday language, Lerdahl and Jackendoff are not interested in artistic aspects of musical structure, but in aspects of musical structure that are usually taken for granted and define the terms in which artistic questions are stated.

Lerdahl and Jackendoff hypothesize that the structure of music results from the interaction between four hierarchical components based on different kinds of units: on the one hand, grouping structure and metrical structure, which determine rhythmical structure; on the other hand, time-span reduction and prolongational reduction, which determine pitch structure. In this article, we will only focus on the first two components, namely on rhythmical aspects of structure, which do not directly involve pitch.

Under Lerdahl and Jackendoff's approach, rhythm results from the interaction between grouping and meter. Grouping structure expresses a hierarchical segmentation of the musical surface into groups, and metrical structure corresponds to an abstract, regular hierarchical pattern of strong and weak beats associated with the musical surface. Lerdahl and Jackendoff distinguish between grouping and meter because groups, unlike beats, need not be regular or receive metrical accents; conversely, beats, unlike groups, do not have duration or inherent grouping. In this section, we will specify these two aspects of rhythmical structure and use our case study to illustrate them.[1]

1.1 Grouping structure of music

Grouping is known to be a general type of cognitive structure, which is common to many areas of human cognition. In the early twentieth century, psychologists of the Gestalt tradition (Wertheimer 1923, i.a.) observed that humans naturally perceive objects as being organized in groups according to several principles such as proximity, similarity or closure. Lerdahl and Jackendoff (1983) propose that (at least some of) these grouping principles, which apply to audition in general, also apply to music specifically, and that the listener uses them to determine their preferred way of segmenting the music. As intuitions about grouping may be vague or ambiguous in case of conflicts between different principles, they call such principles grouping preference rules. We will here focus on how these grouping preference principles can be defined; but note that in addition, Lerdahl and Jackendoff also define a set of grouping well-formedness rules, which state formal

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[1] *The Rite of Spring* by Stravinsky has been analyzed at length by many musicologists (see e.g. Boulez 1966), and is often studied in the artistic context of the early twentieth century, when the avant-garde nature of Stravinsky's music and choreography caused a sensation. My goal here is to take a different perspective and exclusively base my analysis on Lerdahl and Jackendoff's approach. But some of my conclusions find an echo with these studies (see e.g. van den Toorn 1987).

conditions on grouping configurations: according to them, all musical grouping must satisfy a strict, non-overlapping hierarchy of contiguous groups (see Lerdahl and Jackendoff 1983: 37-39). We can distinguish between two types of grouping preference rules: local rules defining the boundaries of groups, based on e.g. similarity or proximity, and global rules defining larger-level grouping, based on e.g. parallelism, symmetry and intensification. Here, I will further detail these two types of rules using as illustrations similarity and parallelism, which primarily govern the grouping structure of our musical case study.

The local grouping rule of similarity states that humans tend to perceive similar objects as grouping together. For example, this principle applied to vision implies that in Figure 1, we instinctively perceive two groups based on similarity in colors: the group of white dots and the group of black dots.

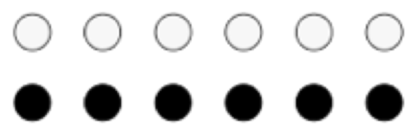

Figure 1 – Grouping rule of similarity applied to vision

In music, given the contiguity constraint on groups noted by Lerdahl and Jackendoff, this principle translates into a rule of change defined in (1).

(1) *Local grouping rule of change*: all else being equal, a transition between two notes may be heard as a group boundary if it involves a change (e.g. in register, dynamics, articulation, length) while the previous and the next transitions do not.
(cf. Lerdahl and Jackendoff 1983: 46)

Rule (1) is illustrated by Lerdahl and Jackendoff's toy examples in Figure 2 (where ^ indicates the relevant transition): in all four passages, it leads us to distinguish between the first three notes and the last two notes based on similarity.

|-----------|--------| |---------|-------| |----------|------| |------------|-------|

Figure 2 – Toy examples of the similarity principle applied to music
(from Lerdahl and Jackendoff 1983: 45)

Specifically, (a) involves a change in register as there is a jump of pitch between the third note and the fourth note. (b) exhibits a change in dynamics (loudness) between the first three notes, which are quiet (as indicated by p – for Italian *piano*), and the last two notes, which are loud (as indicated by f – for Italian *forte*). (c) involves a change in pattern of articulation between the first three notes, which are to be played smoothly and connected (as indicated by the curved line under them), and the last two notes, which are to be performed in a detached way (as indicated by the dots below them). (d) displays a change in length (duration) between the three half notes and the two quarter notes. The groups thus perceived are indicated below the notes using Charnavel's (2016, 2019) notation.

This grouping principle of change allows us to segment our case study into three main groups: group I (the last three measures before *the Augurs of Spring*), group II (the first eight measures of *the Augurs of Spring*, and group III (the next four measures of *the Augurs of Spring*). First, the transition from the end of *the Introduction* to the opening of *the Augurs of Spring*, which is shown in Figure 3, is a very distinctive transition because it involves several changes: a change of instrumentation (in particular, while group I is dominated by the first violins only, all strings start playing together in group II), a change of dynamics (group II is significantly louder than group I), a change of articulation (group I involves the string playing technique *pizzicato*, which consists in plucking the strings, but group II *arco*, which involves using the bow), and a melodic change (after the violin *ostinato* – i.e. repetitive melodic motive, from Italian 'stubborn' – in group I, music begins in group II with insistent repetition of a single dissonant bitonal chord in the strings). Rule (1) thus induces a strong group boundary before the opening of *the Augurs of Spring*.[2]

[2] The distinction between groups I and II created by rule (1) is clearly marked in the scores, since group II corresponds to the beginning of a new passage entitled *the Augurs of Spring*. It is expected that the structure we determine should be partly reflected in the scores, which, as mentioned above, are presumably a partial representation of the mentally constructed entity we are interested in. But the goal here is to provide a more detailed, explicit and empirically adequate structure than the one implied by the scores, which is partly limited by the conventions of music notation. That said, the relation between the perceptual structure and the structure noted in the scores is an interesting topic of investigation in itself.

Group I | Group II

Figure 3 – Transition to the beginning of the Augurs of Spring
(screenshots from video 1 in supplementary material)

Similarly, the grouping principle of change leads us to place a grouping boundary after the first eight measures of *the Augurs of Spring* as shown in Figure 4: as compared to group II, group III (whose beginning is noted as the beginning of passage 14 in the scores) involves different instrumentation (in particular, the English horn (in solo) and the bassoon start playing in group III), dynamics (group III is less loud than group II), articulation (the string playing technique changes again into *pizzicato*) and melody (after the pounding chord in the strings, an *ostinato* starts in English horn over bassoon and cellos).

Figure 4 – Transition to passage 14 in the Augurs of Spring
(screenshot from video 1 in supplementary material)

While the local rule of change leads us to segment our case study into three main groups, the global rule of parallelism allows us to further segment groups I, II and III into subgroups. According to the principle of parallelism, elements that are parallel to each other are perceived as grouping together. In Figure 5, we thus take the three parallel lines to form a single group due to this principle applied to vision.

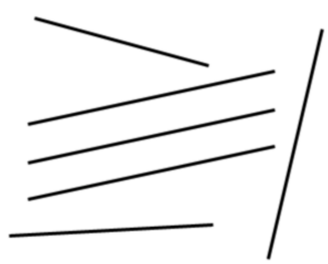

Figure 5 – Grouping rule of parallelism applied to vision

Lerdahl and Jackendoff (1983: 51) adapt the rule of parallelism to music as defined in (2).

(2) *Global grouping rule of parallelism*: when several segments of the music can be construed as parallel, they preferably form parallel parts of groups.
(see Lerdahl and Jackendoff 1983: 51)

Rule (2) is illustrated by the toy examples in Figure 6, where the notes in (a) are most naturally grouped in threes and the notes in (b) in fours, due to motivic parallelism (i.e. each group of notes forms a similar musical ascending phrase).

|---------|---------|---------|---------| |------------|-------------|------------|

Figure 6 – Toy examples of the parallelism principle applied to music (from Lerdahl and Jackendoff 1983: 50)

In our case study, the principle of parallelism is most clearly relevant in group III, where it induces the three-level grouping structure indicated in Figure 7.

Figure 7 – Grouping structure induced by parallelism in group III (screenshot from video 1 in supplementary material)

At the intermediate level, the repetition of the same motive (ostinato) by the English horn and the bassoon induces a perception of four groups (which are explicitly marked in the scores as measures). Furthermore, as repetition is recursive, we can identify two higher-level groups including these four groups. The perception of these two higher groups is reinforced by the motivic repetition by the cellos, which coincides with them.[3] At the lowest level, some degree of motivic parallelism may induce a group boundary within each measure, but I note this level as weak (in grey instead of black) because parallelism here conflicts with another grouping principle proposed by Lerdahl and Jackendoff and defined in (3).

(3) Avoid analyses with very small groups – the smaller, the less preferable.
(see Lerdahl and Jackendoff 1983: 43)

[3] Like Lerdahl and Jackendoff (1983: 37), I assume that a single grouping analysis suffices for all voices of a piece and thus treat our case study as essentially homophonic (see e.g. Rogers 1995 for a discussion about Stravinsky's break with the contrapuntal tradition).

The same reasoning can be applied to the violin melody in group I to justify the two-level grouping structure indicated in Figure 8. This structure however lacks the highest level of group III induced by recursivity of repetition because the motive is repeated an odd number of times here (five times), unlike in group III (where it is repeated four times).

Figure 8 – Grouping structure induced by parallelism in group I (screenshot from video 1 in supplementary material)

In group II (the opening of *the Augurs of Spring* itself), the global rule of parallelism can in principle be applied recursively multiple times, given that the same chord is repeated throughout eight measures, and induce the four-level grouping structure indicated in Figure 9.

Figure 9 – Grouping structure induced by parallelism in group II (screenshot from video 1 in supplementary material)

But in the absence of local cues strengthening it, the intuition about this structure, I assume, remains quite weak; as we will further see when examining metrical structure, the accents (indicated by the symbol >) reinforced by the chords played by the horns even provide conflicting cues as they occur in seemingly random places within the groups induced by the principle of repetition. The only additional clue is the previous passage (group I), which reinforces the perception of the first two levels (which I thus note as darker while retaining the difference between them from Figure 8) due to the interaction between grouping and metrical structures and the fact that in the absence of strong new evidence against it, listeners tend to retain the previous metrical pattern as long as possible (cf. Lerdahl and Jackendoff 1983: 22-25). The details will be explained in the next section concentrating on metrical structure.

1.2 Metrical structure of music

Metrical structure seems less universal than grouping structure. First, unlike grouping, meter is not necessarily present in all music: for example, Gregorian chants do not seem to have metrical structure (Lerdahl and Jackendoff 1983: 18). Second, metrical structure seems more specific to music than grouping: language is the only other cognitive system discussed by Lerdahl and Jackendoff (1983: 85) in which the alternation between strong and weak beats plays a role.

Lerdahl and Jackendoff (1983) propose that metrical structure, like grouping, is governed by two types of principles: well-formedness rules and preference rules. According to well-formedness rules, the abstract metrical grid to which the listener relates musical events must be a regular, strictly hierarchical pattern of beats (which have no duration, but intervals between them form time-spans), and every attack point must be associated with a beat at the smallest level of metrical structure. Preference rules, on which we here concentrate, are the principles that the listener unconsciously uses to determine the most stable metrical structure obeying these conditions.

Like grouping preference rules, metrical preference rules divide into local and global rules. Local rules consist in providing prominent cues for metrical strength such as events (onsets of notes), stress, or length (of e.g. note, dynamics or articulation). The two local rules that will prove most relevant in our case study are defined in (4) and (5).

(4) *Local metrical rule of event*: Prefer a metrical structure in which beats of level L_i that coincide with the inception of pitch events are strong beats of L_i.
(see Lerdahl and Jackendoff 1983: 76)

(5) *Local metrical rule of stress*: Prefer a metrical structure in which beats of level L_i that are stressed are strong beats of L_i.
(see Lerdahl and Jackendoff 1983: 79)

Rule (4) is illustrated by the toy example in Figure 10, where strong beats at the eight-note level occur much more naturally at the attack points of notes (structure (i)) than between them, i.e. at the eighth rest marks noted 𝄾 (structure (ii)). Note that under Lerdahl and Jackendoff's formalism, each row of dots below the music symbolizes a level of metrical structure, and if a beat at a given level L_i is also a beat at a larger level, it is a strong beat of L_i; if it is not, it is a weak beat of L_i.

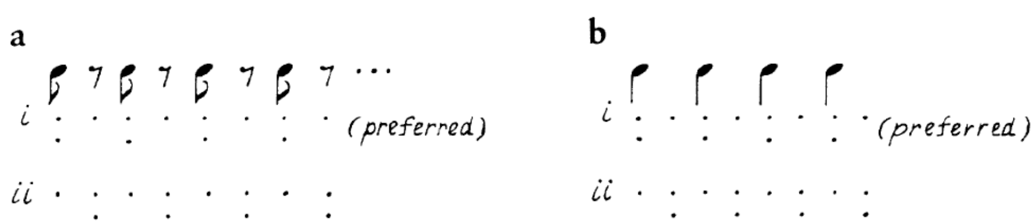

Figure 10 – Toy example of the local metrical rule of event (from Lerdahl and Jackendoff 1983: 76)

Similarly, rule (5) is illustrated in Figure 11, where one most naturally hears structure (i), in which the accented notes (noted with >) are strong beats.

Figure 11 – Toy example of the local metrical rule of event
(from Lerdahl and Jackendoff 1983: 78)

As this will prove crucial in our case study, note that in many cases, these local rules conflict with the global demands of metrical well-formedness, in particular regularity. This can give rise to the phenomenon of syncopation, which can be characterized as a situation where these global demands override local preferences as illustrated by the toy example of Figure 12.

Figure 12 – Toy example of syncopation
(from Lerdahl and Jackendoff 1983: 76)

As explained by Lerdahl and Jackendoff, the metrical well-formedness rules for tonal music require strong beats to be equally spaced (as noted by the equal spacing of dots in the last row in Figure 12). At the same time, as we saw in Figure 10, the local rule of event requires pitch events (vs. rests) to be strong beats (the application of this rule – rule MPR 3 in Lerdahl and Jackendoff 1983: 76 – is noted 3 in Figure 12). Given that all notes are not equally spaced, these two demands are in conflict. Assuming that the global requirements of metrical regularity override local rules, Lerdahl and Jackendoff hypothesize that the local rule of event must be violated twice here (violations are marked with asterisks): both starred notes must appear on a weak beat (and the eighth rests before them thus on a strong beat) for the strong beats to remain equally spaced. Hence, this part of the passage is heard as syncopated. Note that under their analysis, Lerdahl and Jackendoff select one metrical structure for the entire excerpt and never consider resetting the meter locally.

Global metrical rules mainly consist in rules governing the interaction between grouping and meter. Recall that we treat rhythm as arising from the interaction between grouping and meter. For instance, the rhythm of a musical passage is heard differently depending on whether a weak beat groups with the following stronger beat (upbeat) or if it groups with the previous stronger beat (afterbeat). In the former case, grouping and metrical structures are out of phase, while in the latter case, they are in phase. This leads us to define rule (6), the global rule of interaction between grouping and meter that will be most relevant for our case study.

(6) *Global rule of grouping/meter interaction*: Prefer a metrical structure in which the strongest beat in the group appears relatively early in the group.
(cf. Lerdahl and Jackendoff 1983: 76)

In group I of our case study, the combination of this global rule and the local rule of event gives rise to the metrical structure noted (using crosses instead of dots) in Figure 13 below the grouping structure.

```
x x x x   x x x x   x x x x   x x x x x x x x
x   x     x   x     x   x     x   x   x   x
x         x         x         x       x
```

Figure 13 – Metrical structure in group I
(screenshot from video 1 in supplementary material)

The lowest level of the metrical structure is here determined by the notes played by the violins due to the local rule of event (rule (4)). Given that the notes occur at regular intervals, each beat corresponds to a note at that level. The higher levels are determined on the basis of the grouping structure that we assigned to this passage earlier (see Figure 8): rule (6) leads us to place strong beats at the beginning of each group. Given that every group has the same duration at each level of the grouping structure, rule (6) can be systematically obeyed without violating metrical well-formedness.[4] Rule (4) partially reinforces this structure. Given that each beat corresponds to a note

[4] The requirement that strong beats be spaced two or three beats apart at each metrical level in Western tonal music (Lerdahl and Jackendoff 1983: 69) implies that the second metrical level is as strongly perceived as the other levels, even if, as we saw, the intuition for the corresponding grouping level is weaker than for the other grouping levels.

by the violins, rule (4) must apply at every beat, thus making no differentiation. But note that the other instruments also play notes on the first beat, and only then. Rule (4) thus incurs fewer violations if the first beat is a strong beat.

Rules (4) and (6) similarly determine the metrical structure of group III in our case study as shown in Figure 14.


```
x x x x x x x x   x x x x x x x x   x x x x x x x x   x x x x x x x x
x   x   x   x     x   x   x   x     x   x   x   x     x   x   x   x
x       x         x       x         x       x         x
x                 x                 x                 x
x                                   x
```

Figure 14 – Metrical structure in group III
(screenshot from video 1 in supplementary material)

The lowest two metrical levels directly derive from the requirement that every note be associated with a beat at the smallest level of metrical structure, on the basis of the notes played by the bassoon on the one hand and the notes played by the English horn and the cellos on the other hand. The second level is further reinforced by the local rule of event: the even spacing between the notes of the English horn and the cellos ensures that rule (4) is systematically obeyed for these instruments. The three higher levels result from the application of rule (6) based on the grouping structure we determined in Figure 7.

The metrical structure of Group II (the opening of *the Augurs of Spring*) is much more difficult to determine. Recall that under Lerdahl and Jackendoff's approach I adopt here, the term 'metrical structure' refers to a hierarchy of abstract periodicities in time against which musical events are heard. But in Group II, the only clear level of periodicity that can be perceived is induced by the repetitive chord played by the strings; higher-level metrical levels are extremely weak and ambiguous. In fact, the only strong and unambiguous cue to higher-level meter here is the initial transition to the pounding chord at the beginning of the section, and the only following cues (i.e. the accents) directly contradict that metrical analysis. As suggested by a reviewer, it is thus plausible that no real metrical structure is perceived in the actual course of listening this musical excerpt, in the sense that musical events are heard against no higher-level periodicity. Nevertheless, global considerations about the music, as well as choreographic choices in this passage (which will be discussed in the next sections), lead me to hypothesize that the metrical structure indicated in Figure 15 is likely to be the preferred final analysis of group II.

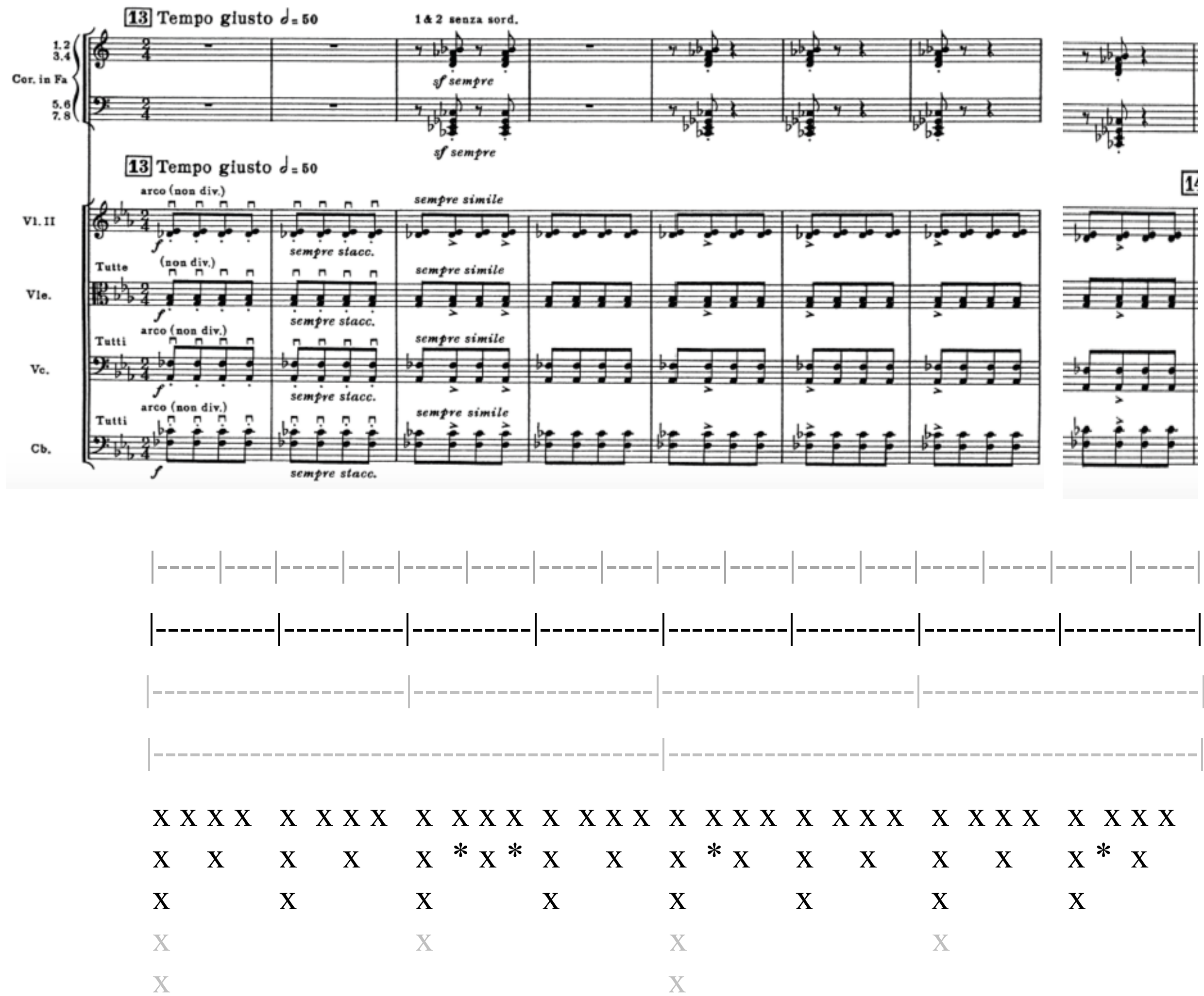

Figure 15 – Metrical structure of group II
(screenshot from video 1 in supplementary material)

As in groups I and III, the lowest level is clearly induced, here by the regular chords played by the strings. As foreshadowed above, the acuity of perception of the higher levels, however, is weakened by two factors. First, recall that the grouping structure of the passage, which is only based on the recursive application of the parallelism rule, remains underspecified and weak due to the absence of local cues reinforcing the abstract pattern. Since the metrical structure is mainly determined by the global rule of grouping/meter interaction (rule (6)), it inherits the weakness of the grouping structure. The only robust aspect of the grouping structure here is the marking of the beginning of group II (see Figure 3), which thus makes the first beat unambiguously strong.

Second, group II includes several prominent local cues for metrical strength, namely the six accents in the strings reinforced by the chords played by the horns. But these cues, which should activate the local rules of stress and event respectively, are highly irregular: only two fall on strong beats (one – in measure 6 – at the second level, and one – in measure 7 – at the third level); the other four accents (in measures 3, 5 and 8) fall on weak beats (at the lowest level) and thus violate the local rules of event and stress (as noted by the asterisks in Figure 15) given the well-formedness requirement of regularity (cf. Figure 12).

Note that an alternative metrical structure could in principle be assumed (and may be actually at play while listening to the piece), which would incur fewer violations of the local rules (4)-(5), as shown in Figure 16.

```
xxxx  x xxx  x xxx  x xxx  x xxx  x xxx  x xxx  x xxx
 x x   x x    x x    x x    x x * x x  * x x    x x
 x     x      x      x      x     x      x      x
 x            x             x            x
 x                          x
```

Figure 16 – Alternative, less preferred metrical structure of group II

In this structure, only two accents, instead of four in the previous structure, fall on weak beats (in measures 6 and 7). This structure is nevertheless predicted to be dispreferred for two reasons. First, as mentioned previously, I hypothesize that listeners tend to retain the previous metrical pattern as long as possible in the absence of strong new evidence against it. The structure in Figure 16 is thus predicted to be disfavored since it is the structure in Figure 15 that corresponds to the previous metrical pattern (at least with respect to the three lower levels, see Figure 13) and the new evidence against it (namely the accents) is not strong (out of 16 beats, only 4 beats are thus reinforced, and two violations remain). Second, this structure conflicts with the global rule of grouping/meter interaction, since it makes all groups start on a weak beat. We certainly concluded that the intuition for grouping structure is quite weak; nevertheless, this is not the case of the biggest group (group II itself), whose beginning is very clearly marked (see Figure 3): in this structure, rule (6) is thus strongly violated once, and (more or less) weakly violated fifteen times. The structure in Figure 15 is thus preferred over the structure in Figure 16, and the four violations of the local rules of stress and accent it involves, which are overridden by global considerations such as the constraint on regularity and the preferences for metrical continuity and for grouping/meter correspondence, give rise to syncopation effects.

Finally note that the structure proposed in Figure 15 is not perceptually homogenous. On the vertical level, the two higher levels are less salient than the lower ones, especially the highest one, for two reasons. First, the two higher levels are only determined based on grouping/meter interaction, and as we saw, the two higher corresponding grouping levels are weakly perceived, since they are only induced by the recursivity of repetition. The lower levels, however, are also induced by local cues (the notes at the lowest level) and by the previous metrical structure. Second, higher metrical levels are less prominent in general. As Lerdahl and Jackendoff (1983: chapter 4) suggest, the further away from the tactus level a metrical level is, the less prominent it is. The tactus level is one specially designated metrical level, which is the perceptually most prominent metrical level (i.e. the pulse that one most naturally coordinates foot-tapping with and that is usually used by dancers to make their steps) and cannot be too far away from the smallest metrical level. Which metrical level is perceived as the tactus level may be subject to variation, but whether we here perceive it to be the third level (as implied by the measure notation) or the second level (see further discussion in section 3.1), we can conclude that the fourth level and especially the fifth level are less prominently perceived.

On the horizontal level, the perception of the metrical (and grouping) structure of group II gradually fades away, given that it is mainly guided by the structure of the previous passage.[5] For instance, the syncopation effects are perceived more strongly in measure 3 than in measure 8, where the perception of the pulse is the weakest (before becoming stronger again in group III); at the end of group II, it is conceivable that the structure of Figure 16 overrides that of Figure 15 – or even that no proper metrical structure is perceived at all anymore. As we will see in section 3, the accompanying dance can however modify the perception of the structure by reinforcing at least some of the structural levels. In fact, it seems that some aspects of the choreographies under study are precisely meant to help disambiguate the metrical structure because it is so difficult to process in the music. To explain this, we first need to determine how to identify the rhythmic structure of the dance itself, to which the next section is dedicated.

[5] This type of hypothesis is not considered by Lerdahl and Jackendoff that generally propose a single analysis for a full passage. Here, I nevertheless suggest that a change of perceptual analysis may happen during a single passage, based on the hypothesis that local conflicting considerations may override global considerations over time.

2 Adapting Lerdahl and Jackendoff's 1983 rhythmical analysis to dance

The goal of this section is to examine to what extent we can apply to dance Lerdahl and Jackendoff's rhythmical principles of music, which we have just reviewed and used to analyze our case study: are these grouping and metrical principles relevant for visual perception of dance?
Using three choreographies of our passage from *the Rite of Spring* as illustrations, I will show that Lerdahl and Jackendoff's 1983 rhythmical principles of music can be adapted to dance. More generally, I argue that just as in the case of music, taking a cognitive approach to dance can lead us to reach a formal description of the dance intuitions of an observer, based on the assumption that a dance piece is a mentally constructed entity.[6] The goal is thus to build a basic grammar of dance (which does not regulate, but underlie artistic effects) in order to specify the largely unconscious knowledge that allows an observer to organize and make coherent the surface patterns of dance. Like before, I will here focus on rhythmical structure, and investigate how the differences between music and dance perception (esp. in modality) alter the formulation of the rhythmical principles that we examined earlier. Retaining the hypothesis that rhythm results from the interaction between grouping and meter, I will first examine the grouping structure of dance by reviewing principles identified in previous work (Charnavel 2016, 2019) and applying them to our case study. Then, I will investigate to what extent metrical structure also applies to dance and how its interaction with grouping gives rise to rhythmical properties.

2.1 Grouping structure of dance

As we mentioned in section 1.1, grouping is a general cognitive structure that applies to many areas of human cognition. We can thus reasonably assume that it also applies to dance. Following Charnavel (2016, 2019; see also Miura et al. 2010), I further assume that just as in the case of music, we can distinguish between well-formedness and preference grouping principles in dance. Dance, like music, happens in time, so that it must also obey the requirement that all grouping satisfy a strict, non-overlapping hierarchy of contiguous groups. Furthermore, we can hypothesize that an observer unconsciously uses various principles to determine her preferred way of segmenting the dance: just like music, dance seems subject to ambiguous interpretations, which

[6] Just as in the case of music, I will thus concentrate on perception, which is more widespread than composition or performance, and I will set aside the potential effects of experience in a specific dance idiom.

makes the preference rule formalism as adequate for dance as for music. Below, I define and illustrate some of these preference rules.

Recall that grouping preference rules divide into local rules defining the boundaries of groups and global rules defining larger-level grouping. Global rules, which are more abstract, can directly be adopted from music to dance. But local rules need to be adapted to dance by taking into account some relevant differences with music. In particular, dance positions, unlike musical notes (which can be separated by silence) are necessarily continuous (in space) due to physical constraints.[7] This affects the way the rule of proximity can be formulated and implies that some aspects of it can be reformulated using the notion of speed (see rule (7)). Furthermore, the perceptual features relevant to grouping rules in dance are in the visual modality. The formulation of the rule of similarity, which we will use as main example of local rule here, thus requires identifying the relevant counterparts of auditory features in the visual modality (cf. Eitan and Granot 2006); in that sense, note that the formal description of dance based on music raises issues similar to the ones raised by the formal description of sign languages based on spoken languages.

Observing that the physical signal of dance consists in changes of positions in time, Charnavel (2016, 2019) distinguishes between features of the dancer position (location, configuration, orientation and weight support) and features of the movement (direction, speed, quality) (cf. von Laban 1928, Napoli and Kraus 2017). This hypothesis leads Charnavel (2016, 2019) to translate the musical rule of change in (1) into the dance rule of change in (7), which only differs with respect to the parameters of change.

(7) *Local grouping rule of change*: all else being equal, a transition between two positions may be seen as a group boundary if it involves a change (e.g. in moving entity, orientation, weight support of the body position, or in direction, speed, quality of the movement) while the previous and the next transitions do not.
(cf. Charnavel 2016: 18-23; Charnavel 2019: 4)

Rule (7) can be illustrated by parts of each of the choreographies under study. Note that in this section, we focus on dance itself, so that videos should be watched without sound; for ease of exposition, I will nevertheless refer to the relevant passages using the musical notation given the

[7] But as noted by an anonymous reviewer, the use of videos and lightning in contemporary dance can lead the audience to perceive dance positions as discontinuous. In those cases, the formalism used for music can be directly adopted for dance.

absence of conventional dance notation for these choreographies.[8] First, Nijinsky's choreography in group III (i.e. the dance happening in measures 1-4 of passage 14) exemplifies how a change of movement direction can induce a group boundary. In measures 1-2, the five dancers in circle move in one direction, while in measures 3-4, they move in the other direction. This change of direction leads the observer to perceive a group boundary at the position (called P2 in Figure 17) corresponding to the transition between measure 2 and measure 3 as shown in Figure 17, where the relevant positions are illustrated with screenshots of the video.

P1 P2 P3

|----------------------------|----------------------------|

|---|

Figure 17 – Change of direction in Nijinsky's group III (screenshots from video 2 in supplementary material)

Second, Béjart's choreography in group III illustrates how a change of body orientation can induce a group boundary. In the first two positions held during the first two measures of passage 14 (P1 and P2 in Figure 18),[9] the torsos of the dancers are oriented towards the left (from the observer's perspective), but in the last two positions held during measures 3-5 of passage 14 (P3 and P4), as well as the first position after group III (P5), the dancers are oriented towards the observer.[10] We thus perceive P3 as a transition between two groups, in accordance to rule (7).

[8] As mentioned by an anonymous reviewer, even if we do not have notations for the choreographies under study, we do have access to some of the choreographers' intentions. It would be interesting to investigate whether these intentions (which the dancers are usually aware of) are reflected in the perceived structures of the dance.

[9] In this passage of Béjart's choreography, the dancers hold several poses successively. The choreography thus seems to artificially lead the observer to perceive the positions as non-continuous in parallel to musical notes.

[10] Working with a video here, we have to rely on the way the performance was filmed. I assume the camera angle is the same as the spectators'.

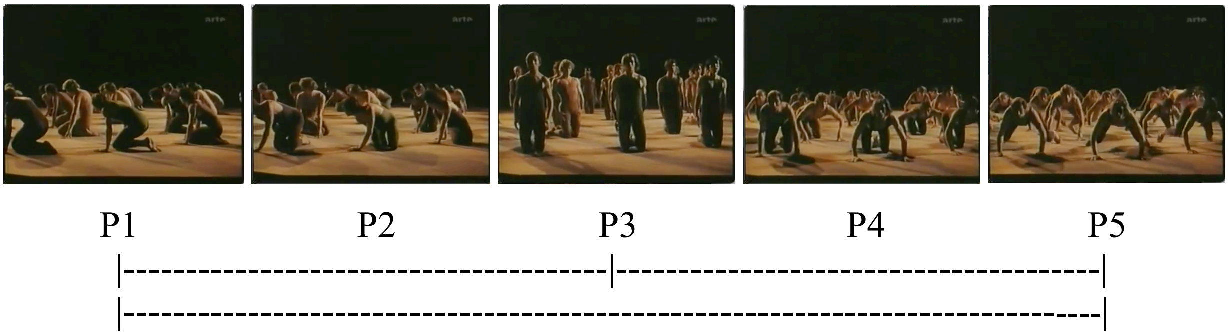

Figure 18 – Change of direction in Béjart's group III (screenshots from video 3 in supplementary material)

Note that in general, the perception of group boundaries may be more or less acute depending on the relative strength of the change. For instance, a 180-degree orientation change would probably induce a stronger group boundary than the 90-degree orientation change in Figure 18. Furthermore, as argued in Charnavel (2019), some types of change may be perceptually more salient than others. But specifying the strength scale of various types of change requires establishing a normative state for each type of change and determining how the intensities of various types of change compare. For instance, in order to predict the comparative strength of the group boundaries induced by the direction change in Figure 17 and the orientation change in Figure 18, we must not only clarify how to compare the intensity of a direction change with that of an orientation change, but also evaluate whether one of these two types of change is in principle more salient than the other. These types of issues, which are experimentally addressed in Charnavel (2019) (cf. Deliège 1987 for music), are especially relevant when several types of change give rise to conflicting segmentations of the movement. As this is not the case in our case study, I will not further delve into the issue here.

In Figures 17 and 18, we have applied rule (7) with respect to some parameter of the position (orientation) or the movement (direction) of the dancers, without distinguishing between each of the dancers, who all perform the same moves in these passages. But rule (7) can also be applied by comparing the moves of the dancers. For example, the transition between group II and group III in Bausch's choreography is marked by the fact that one dancer starts her own move while the other dancers keep performing the same moves, as schematized in Figure 19.

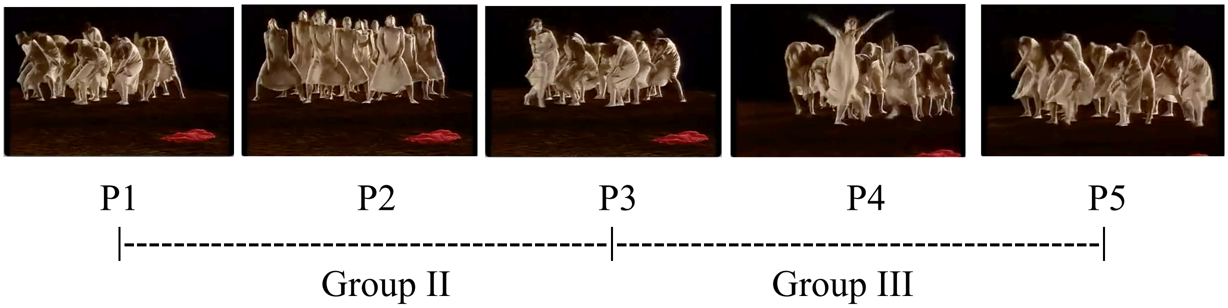

Figure 19 – Groups II-III in Bausch's choreography (screenshots from video 4 in supplementary material)

Between positions P1 (at the beginning of group II) and P3 (at the beginning of group III), all the dancers are doing the same moves. But starting at P3, one of the dancers breaks away from the rest of the group and starts doing her own move until P5 (end of group III). We thus perceive group III as distinct from group II because we apply the rule of change, not with respect to one specific feature, but with respect to the moves of the dancers more generally: they are the same in group II, but different in group III.

Beside the local rule of change, the global rule of parallelism is the other main rule used to segment the choreographic passages under study. Given that it does not involve specific features, it can straightforwardly be adopted from the definition given for music in (2) as in (8).

(8) *Global grouping rule of parallelism*: when several segments of the dance can be construed as parallel, they preferably form parallel parts of groups.

For example, the application of this principle allows us to segment Bausch's group II into subgroups as shown in Figure 20. In this group, the same sequence of moves is repeated four times by all dancers, which leads to the perception of four groups (P1, P2, P3 and P4 correspond to the first position of the sequence of moves each time). Just as in the case of the music (see Figure 9), the question arises as to whether the recursivity of repetition induces the perception of two higher groups indicated in grey in Figure 20.

```
    P1            P2            P3            P4            P5
    |-------------|-------------|-------------|-------------|
    |---------------------------|---------------------------|
    |---------------------------------------------------------|
```

Figure 20 – Grouping structure induced by parallelism in group II of Bausch's choreography (screenshots from video 4 in supplementary material)

Rules (7)-(8) thus lead us to structure Bausch's whole passage as indicated in Figure 21.

```
------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
------------------------------|------------------------------|------------------------------|
           Group I                       Group II                      Group III
```

Figure 21 – Grouping structure of Bausch's choreographic passage under study based on the local rule of change and the global rule of parallelism

Group I is not divided into subgroups as the dancers are not performing distinctive moves, but slowly walk towards each other to form a group.[11] However, the transition between group I and group II is strongly marked by the change in types of moves (all dancers walking differently vs. all dancers performing the same sequence of dance moves). As for group III, the group of dancers is roughly performing the same four sequences of the same moves as in group II, which gives rise to the same four subgroups. The different dance of the dancer who breaks away from the others in this group (see Figure 19) can be similarly structured: during every sequence of moves performed by the group of dancers, she is doing a different type of move (movement towards the center, *rond de jambe*, turn, movement to the right), which reinforces the grouping induced by the moves of the other dancers. However, the fact that the four moves of the solo dancer are different prevents the observer from perceiving two-higher level groups based on recursivity of repetition in the moves of the other dancers (cf. grey level in Figure 20). Given the otherwise parallel structure of group II and group III, I thus hypothesize that group II is not perceived as including these two

[11] This slow formation of a group of dancers creates some tension, which may be relevant to other, non-rhythmical aspects of structure (which may be the counterpart of pitch structure). I leave the examination of the relevance of tension in dance structure for further research (see also fn. 31).

higher-level groups either (or more exactly, given that group II comes before group III, the potentially weak perception of these groups is not reinforced, and therefore further weakened, by the following sequence). Finally note that I further assume that groups are not further subdivided on the basis of rule (3), according to which analyses with very small groups are dispreferred.

The grouping structure of Nijinsky's choreography, indicated in Figure 22, also heavily relies on the global rule of parallelism (8).

```
------------------------------|---|---|---|---|---|---|---|---|--------------|--------------|
------------------------------|-------|-------|-------|-------|--------------|--------------|
------------------------------|---------------|---------------|--------------|--------------|
------------------------------|-----------------------------|-----------------------------|
           Group I                       Group II                     Group III
```

Figure 22 – Grouping structure of Nijinsky's choreographic passage under study

Rule (8) is mainly used in group II, where the dancers in circle repeat the same sequence of moves (i.e. one bigger jump followed by three smaller jumps) eight times, which induces a segmentation into eight groups. Recursivity of repetition could in principle induce two higher-level grouping levels (with four and two groups, respectively). But it remains unclear whether they are actually perceived, especially given the arm movements marking the musical accents in random places of the groups (see further discussion in section 3.1). The structure of group III is also partially induced by parallelism given the two symmetrical sequences of moves performed by the dancers in circle (eight jumps with change step and arm movements at the end), first in one direction, and then in the other direction. As shown in Figure 17, the local rule of direction change reinforces this grouping structure. Finally, the rule of change leads us to clearly identify each bigger group: the transition from group I to group II is marked by the fact that after remaining still, the dancers start jumping, and the transition from group II to group III by the fact that after jumping up and down, the dancers start moving in circle; the unity of group III is further strengthened by the fact that each dancer comes back to the same position at the end of group III (closure).

Finally, the grouping structure of Béjart's choreographic passage, which is shown in Figure 23, also partially relies on parallelism, specifically within group II.

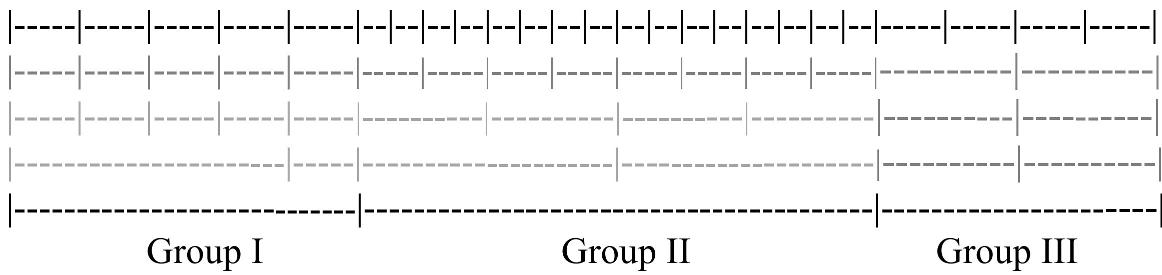

Figure 23 – Grouping structure of Béjart's choreographic passage under study

In group II, all the dancers perform the same jump sixteen times, which may lead us to perceive sixteen groups, although this perception remains weak due to rule (3). Just as in the case of music (cf. Figure 9), recursivity of repetition can in principle induce three higher-levels of grouping (including eight, four and two groups, respectively, as indicated in grey in Figure 23); but in the absence of local cues, it remains unclear whether this structure can actually be perceived. In both group I and group III, the grouping structure is determined based on the rule of change. In group I, (some of) the dancers take a new position (with weight shift), which they hold, five times;[12] this induces a segmentation of group I into five groups. In group III, all the dancers take a different position (with weight shift) four times, which leads us to perceive four groups; furthermore, the change of orientation at the third position may induce a higher-level grouping boundary (marked in grey) as discussed in Figure 18 above. Finally, the transitions between groups I, II and III, are marked by global changes: while in groups I and III, the dancers successively take new positions and held them for a small amount of time, in group II, they all perform the same jump without any break in between.

2.2 Metrical structure of dance

In the previous section, we saw that it is appropriate to apply grouping rules to dance, as long as the specific perceptual features of dance are taken into consideration. The goal of this section is to determine to what extent metrical structure is also relevant to dance. As mentioned earlier, Lerdahl and Jackendoff assume that metrical structure is less common in human cognition and seems more

[12] More precisely, all dancers are on their knees at the beginning of Group I, and the ones after the others (in four steps), they take the same new position (putting their hands on the floor), and then, they all take together a new position by lifting their knees. The specificity of the last position (taken by all dancers together) as compared to the first one taken by the dancers in four steps, may lead us to place a higher-level group boundary between the fourth and the fifth group of group I, which I tentatively note in grey in the next to last level of Figure 23.

specific to music (and language); but interestingly, they also briefly mention dance in describing the specific Macedonian metrical idiom as reported in Singer's 1974 study of Macedonian dance. In accordance to this suggestion (see also studies on music-induced movement such as Toiviainen, Luck and Thompson 2010 and references therein), I hypothesize that metrical structure can apply to dance: it is possible (although less systematic than in music, as we will see) to extrapolate a metrical grid (i.e. a regular, strictly hierarchical pattern of beats) from (at least some parts of) a dance event; and to determine the most stable metrical structure, the observer unconsciously uses various preference principles, some of which I now describe.

Like dance grouping rules and musical metrical rules, dance metrical rules can be divided into local and global principles. Local rules, which consist in prominent cues for metrical strength, can be transposed from music to dance by taking into account the perceptual features of dance. For example, the notions of event and stress crucial to rules (4)-(5) must be adapted to dance (see (9)-(10)): an event is not a note, but a distinctive move; stress is not marked by high intensity in sound, but high intensity in force or amplitude of the movement.

(9) *Local metrical rule of event*: Prefer a metrical structure in which beats of level L_i that coincide with the inception of dance events are strong beats of L_i.

(10) *Local metrical rule of stress*: Prefer a metrical structure in which beats of level L_i that are stressed are strong beats of L_i.

The rule of stress is most clearly illustrated by group II of Nijinsky's choreography, which, as we saw, consists of eight series of one bigger jump followed by three smaller jumps (see discussion of Figure 22). This gives rise to the metrical structure indicated in Figure 24 (recall that videos should be watched in silence in this section in order to study the structure of dance independently of the accompanying music).

```
x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x
x       x       x       x       x       x       x       x
```

Figure 24 – Metrical structure of Nijinsky's group II

The lower metrical level arises from the requirement (adapted from music) that every event (a jump here) be associated with a beat at the smallest metrical level. The higher level is induced by the rule of stress: given that one in four jumps is performed with higher intensity (the jump is higher and the force towards the floor is more important), it must be a strong beat. The regularity of all jumps ensures that the demands of metrical well-formedness are obeyed in this structure.[13] Note that even if Béjart's choreography also involves regular jumps in group II, it does not induce a proper metrical grid like Nijinsky's choreography. The reason for that is that the sixteen jumps of Béjart's dancers in group II are undistinguishable, so that only one metrical level can be inferred. But as mentioned earlier, metrical well-formedness requires hierarchy (not just periodicity). That is not to say, however, that the regularity of the jumps in Béjart's group II has no effect on metrical structure; although it does not induce a dance metrical structure, I will argue in section 3.1 that it is relevant to the dance-music metrical structure.

Just as for grouping, global metrical rules can be directly adopted from music. In particular, rule (6) repeated as (11) below is highly relevant to our case studies.

(11) *Global rule of grouping/meter interaction*: Prefer a metrical structure in which the strongest beat in the group appears relatively early in the group.

First note that the application of rule (11) reinforces the metrical structure of Nijinsky's group II indicated in Figure 24 since each of the strong beats corresponds to the beginning of a group (see Figure 22).

Given the grouping structure we determined in Figure 20, rule (11) similarly induces the metrical structure indicated in Figure 25 for Bausch's group II.

```
x   x   x   x   x   x   x   x   x   x   x   x   x   x   x   x
x               x               x               x
```

Figure 25 – Metrical structure of Bausch's group II induced by global rule (11)

The lower level is based on events (namely, weight shifts – only the third beat in each group of fours does not correspond to a weight shift), and the second level on the interaction with grouping: each hypothesized strong beat appears very early in the group.[14]

But in Bausch's group II, unlike in Nijinsky's group II, local rules conflict with the global meter/grouping interaction rule beyond the first level of the structure. First, the highest level of

[13] Here, I do not adapt to dance Lerdahl and Jackendoff's well-formedness rule according to which strong beats must be spaced two or three beats apart at each metrical level in Western tonal music (see fn. 4).

[14] Given the presence of an anacrusis in the dance (which will be discussed in fn. 26), each strong beat is not the actual beginning of the group, but the first prominent event in the group.

energy does not occur on the first move in each subgroup, but on the fourth (last) one, which involves not only a weight shift, but also a high-amplitude arm movement towards the floor. The local rule of stress (rule (10)) thus induces a metrical structure in which the fourth position, instead of the first position of each subgroup is a strong beat. Second, the dancers hold the pose on the second position of each subgroup (in second position, i.e. with bent knees and both feet apart and turned out) twice longer than in the other positions. I hypothesize that this induces strong beats due to the local rule of length specified in (12), which I adopt from Lerdahl and Jackendoff (1983: 80-85).[15]

(12) *Local metrical rule of length*: Prefer a metrical structure in which beats of level L_i that occur at the inception of relatively long dance events are strong beats of L_i.

Change of head direction (towards the ceiling and towards the floor) on the second and fourth beats of every four beats at the second metrical level reinforces these two patterns due to the local rule of event (rule (9)).[16] Finally, I assume that the fourth position is perceived as stronger than the second one, due to the rule of stress being applied more intensively (in the fourth position) than the rule of length (in the second position) here. In sum, the local metrical rules thus give rise to the metrical structure indicated in Figure 26.

```
x x x x x x x x x x x x x x x x
  x   x   x   x   x   x   x   x
      x       x       x       x
```

Figure 26 – Metrical structure of Bausch's group II induced by local rules

This metrical structure conflicts with that of Figure 25. A systematic, experimental testing of the perception of various observers would help us determine which of the structures in Figure 25 or 26 (or variants of those, depending on whether two or three levels are included) is generally preferred, especially whether it is the first position or the fourth position in each subgroup that is perceived as the strongest beat.[17] Based on my own intuition, I suggest that the structure in Figure

[15] I did not specify the local rule of strength for musical metrical structure because it is not exemplified in our case study. But as briefly mentioned in section 1.2, Lerdahl and Jackendoff include length (of e.g. note, dynamics or articulation) as a prominent cue for metrical strength in music. I here adapt this rule to dance.

[16] Although there is no change of head direction between the fourth and the first beats, the dancers bounce their heads on the first one. To the extent that this head bounce induces the application of the local rule of event, it is therefore the only application of a local rule that supports the structure in Figure 25 rather than that in Figure 26.

[17] This could be tested in many different ways. For example, participants could be asked to tap to the beat while watching the dance passage (after familiarizing themselves with it); to determine the different metrical levels, they

25 is entertained in the first phase of the group, giving rise to syncopation effects on the second and fourth positions (see further discussion in section 3.2); the analysis in Figure 26, under which the initial beat of the section is weak, is dispreferred at first not only because it violates the global rule of grouping/meter interaction (strongly so at the beginning where the boundary between groups I and II is strongly marked), but also because it entails that there is a preceding strong beat unmarked by any event, which would thus violate the local rule of event. But as the dance of group II progresses and the perception of the group boundaries fades away, the structure in Figure 26 ends up being more prominent: ultimately, the new, local evidence provided by accents seems to override the structure induced by more abstract and global considerations.[18] In section 3, we will nevertheless see how the accompanying music reverses this perception by further supporting the analysis of Figure 25.

The conflict between the metrical structures in Figures 25 and 26 does not arise, however, in Bausch's group III in which the dancers do not perform the stressed arm movement although the rest of their moves remains identical. Furthermore, the dance of the solo dancer reinforces the grouping structure leading to the metrical structure in Figure 25 (see discussion below Figure 21) and is more salient than that of the other dancers, as she is in front of them and partially hides them.

We have thus seen that both local and global metrical rules can be relevant and give rise to a metrical structure in dance. In particular, we have identified a two-level metrical structure in groups II-III of Bausch's choreography and in group II of Nijinsky's choreography. No metrical structure, however, can clearly be inferred from the rest of our case studies. In Béjart's choreography, the issue discussed for group II holds throughout the passage: regular moves can lead us to identify one metrical level, but neither local nor global considerations can induce other levels of metrical structure; the only higher grouping level that could generate application of the global grouping/meter interaction rule (11) is the one inducing the distinction between groups I, II

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could then be asked to find a slower or/and quicker pulse. Another possibility would be to add an audible beat to the dance (reflecting various metrical structures and various metrical levels) and ask participants to rate the appropriateness of each beat pattern.

[18] Alternatively, we could assume that the perception of the grouping structure also evolves, with the group boundary shifting from before the first to before the fourth of every four positions, thus aligning with the metrical structure shown in Figure 26. Again, experimental testing of the perception of various observers could discriminate between these possible analyses.

and III, but it cannot induce a metrical level as the time spans of the groups are neither regular, nor sufficiently short. As a flat metrical structure is no proper metrical structure, I conclude that an observer cannot extrapolate any metrical structure from Béjart's choreographic passage in the absence of music.

A similar problem arises in group III of Nijinsky's choreography, where the dancers' jumps are all of the same intensity, unlike in group II, so that the local rule of stress cannot be applied. Unlike in Béjart's choreography though, rule (11) can be applied within group III due the grouping structure induced by parallelism and direction change (see Figure 22), which could give rise to the metrical structure shown in Figure 27.

```
x x x x x x x x x x x x x x x x x x
x                 x
```

Figure 27 – Metrical structure of Nijinsky's group III

Given that the two groups of the same length, this structure obeys the metrical constraint of regularity. But I suggest that the perception of this structure is weak at best, given that the hypothesized strong beats are not sufficiently close to each other. As for group I of Nijinsky's and Bausch's choreographies, they clearly lack metrical structure given the absence of distinctive moves (we already saw they lack grouping structure, see Figures 21-22).

By comparing the discussions in sections 1.2 and 2.2, we notice a clear difference between the metrical structures of the music and the dance in our case study. While I assigned a metrical structure to the whole musical passage, I identified a metrical structure only in some parts of the choreographies. In spite of the extremely limited size of our sample of examples,[19] which cannot therefore be taken as evidence, I hypothesize that this difference is representative: although a metrical structure can in principle be extrapolated from dance, this happens less systematically than in music; in other words, it seems that a hierarchy of periodicities is less necessary in dance than in music perception. I further suggest that the modality difference in perception between music and dance is responsible for this.

This hypothesis is supported by various types of psychological studies. Some reveal a modality effect in the reproduction of rhythm (see e.g. Glenberg and Jona 1991 and references therein) or

[19] Furthermore, a potential bias in our example is that the choreographies were created based on a pre-existing music with a rich metrical structure as discussed in the main text below.

in the synchronization with a beat (see Patel et al. 2005): auditory rhythms are reproduced or synchronized with more accurately than visual rhythms. Others, which investigate rhythm perception when auditory and visual information conflicts, show that audition dominates temporal processing while vision dominates spatial processing (see e.g. Repp and Penel 2002), and argue that rhythm is always encoded in the auditory modality (see e.g. Guttman, Gilroy and Blake 2005): incongruent auditory information interferes with rhythm discrimination more significantly than visual information, whether rhythm is conveyed by auditory or visual stimuli.

From these two arrays of facts, we can conclude that in general, we prefer to associate metrical structure to an auditory stimulus than to a visual one. For dance, this has two opposite consequences (from the perspectives of perception and production), which reinforce each other. First, given that memory for visual rhythm is inferior to memory for auditory rhythm (Glenberg and Jona 1991), I hypothesize that the perception of a metrical structure in dance requires more local cues than in music. For example, I assumed that while the metrical structure of our musical group II can be partly inferred from the structure of group I, it is unlikely that the metrical structure of Nijinsky's group III can be inferred from the structure of group II.

Second, dispreference for visual (vs. auditory) rhythm implies that we tend not to convey rhythm in the visual modality, at least if the auditory modality is available. Given that dance is usually accompanied by music, this means that metrical cues are more likely to be produced in the music than in the dance. Note that this raises the question of the effect of the accompanying music on the metrical structure of dance from the perspective of the production (as the choreographies under study were created on a pre-existing music). On the one hand, it may be the case that local metrical cues are less likely to be produced in dance in the presence of an accompanying music than in its absence, since it is sufficient to induce a metrical structure from the music. This first hypothesis would predict that dance without a sound track (or dance created before the accompanying music) should be metrically richer than dance with a sound track. On the other hand, we could conversely suppose that a metrical structure is more likely to be explicit in dance in the presence of an accompanying music because we tend to favor match between dance and music (see section 3). This second hypothesis would conversely predict that dance in silence would be metrically less rich than dance in music. These two hypotheses rely on different assumptions about the necessity of a metrical structure: the former implies that a metrical structure must be present in music, dance and dance-music events (and it can be expressed in music or/and in dance); the latter implies that a metrical structure need not be present in dance, unlike in music. Examining the metrical properties of dance without (pre-existing) music should thus allow us to determine to what extent metrical structure is necessary to dance itself or to an event involving dance. Furthermore, it would be interesting to compare the metrical properties of dance without music in the hearing community and in the deaf community. It would allow us to determine whether the metrical difference between the visual and the auditory modalities is absolute (the visual modality is not conducive to expressing meter in principle) or contrastive (the visual modality is less conducive to expressing meter than the auditory one). I leave all these questions for future research as we here focus on the perspective of perception.

From that perspective, we can conclude that a metrical structure can be perceived in dance on the basis of metrical rules similar to musical rules, although it seems to be less systematically perceived in dance (alone) than in music. This does not mean, however, that dance cannot specifically contribute to metrical structure: in the next section, I will argue that dance does influence the perception of the metrical structure of a dance-music event. More generally, my goal is to show that when we perceive dance and music together, we extrapolate a single rhythmic structure, to which the structures of both music and dance contribute differently due to their modality. My argument will be based on the study of the first eight measures of *the Augurs of Spring* (group II) in the three choreographies under study.

3 Rhythmical analysis of dance-music events: the single structure hypothesis

In sections 1 and 2, I have argued that the same kinds of organizational principles are used for the perception of rhythm in music and dance: local and global principles of grouping and meter, which interact to create rhythm. This supports my hypothesis that music and dance are part of the same cognitive system, although they are perceived in different modalities, just like sign and spoken languages are part of the same abstract linguistic system.

This also raises the question of what type of structure(s) is inferred when dance and music are perceived together. This question, to which this last section is dedicated, is all the more pressing because dance and music naturally tend to be performed together. Dance is usually accompanied by music, and in most cultures, music and dance have evolved together (Arom 1991; Cross 2003; Wallin, Merker and Brown 2000). The specific artistic effect produced by dance performed in silence (e.g. *Trio A* by Yvonne Rainer) or by dance dissociated from music in some contemporary pieces (e.g. Cunningham's work; see e.g. discussion in Fogelsaner and Afanador 2006) further suggests that dance is naturally performed to music.[20] Moreover, psychological studies show that music and movement influence each other. On the one hand, music induces movement: when listening to music, we tend to spontaneously move our body along with it (see Lesaffre et al. 2008, Keller and Rieger 2009, Toiviainen, Luck and Thompson 2010, Janata et al. 2011, i.a.). On the other hand, movement seems to affect beat perception (see Todd, O'Boyle and Lee 1999; Todd, Cousins and Lee 2007; Phillips-Silver and Trainor 2005, 2007; Trainor, Gao, Lei, Lehtovaara and Harris 2009; Lee, Barrett, Kim, Lim and Lee 2015; i.a.).

Given this natural link between music and dance, I here hypothesize that when we perceive a dance-music event, we perceive a single rhythmical structure, to which both musical and dance structures contribute.[21] To understand the type of structure induced by a dance-music event, we must thus determine how the grouping and metrical structures of music and dance, as we described them in the previous sections, combine to give rise to a dance-music structure.[22]

The natural connection between music and dance just mentioned also suggests that as observers, we naturally tend to match the structures of dance and music (see Krumhansl and Schenck 1997, Mitchell and Gallaher 2001, i.a.). That's why a total disconnect between dance and music as envisioned in Merce Cunningham's choreographic work (in collaboration with the musician John Cage) seems very difficult to the observers that spontaneously try to find some connection between the dance and the music (see Fogelsaner and Afanador 2006). But just as grouping or metrical principles within a single system (e.g. dance, or music) can conflict to some extent, as we saw, and create richer or ambiguous structures, I hypothesize that some degree of mismatch can similarly occur between dance and music. To determine the structure of a dance-music event, I will thus examine what type of structure arises not only when structural aspects of the dance match the

[20] Interestingly, experimentation in producing works in which dance and music (cf. film and music) seem incongruent started around the time of our case study (at the beginning of the twentieth century, esp. with the Ballets Russes and the Parisian avant-garde).

[21] This hypothesis is consistent with the more general observation that incongruent visual and auditory information tend to be perceived as congruent (see e.g. the phenomenon of visual or auditory captures: see Bolivar, Cohen and Fentress 1994; Iwamiya 1994; Lipscomb and Kendall 1994, i.a.). But under our hypothesis, dance and music are part of the same cognitive system. The structure resulting from their combination does not just result from capture, but reflects a deeper, intrinsic connection between dance and music.

[22] The emerging field of choreomusical analysis, which aims at theorizing the relationship between dance and music instead of studying them separately, is of particular relevance here (see Hodgins 1992, Jordan 2000, Leaman 2016, i.a.).

music, but also when they mismatch.[23] I will mainly illustrate match effects using Nijinsky's and Béjart's choreographies, and mismatch effects using Bausch's choreography, focusing on group II (videos should obviously be watched with sound in this section).

3.1 Match effects

A total match between dance and music, which would involve perfect correspondence between all grouping and metrical levels, would presumably make the dance-music structure identical to both the dance and the music structures taken independently, and easier to perceive as both structures would reinforce each other. Nevertheless, such a case is very rare: in actual choreographies, total match would be artistically uninteresting; and as we will see, the modality difference between dance and music makes total match unlikely even in natural occurrences of dance-music (such as music-induced movement). Thus, I will here concentrate on partial match between dance and music structures, namely cases in which some level(s) of the grouping or/and metrical structure of music find(s) a counterpart in the dance.

In such cases, I will argue that the main effect obtained is disambiguation.[24] As we saw, the preference rule formalism is meant to capture the fact that structural interpretations in dance and music can be ambiguous. Under Lerdahl and Jackendoff's approach, ambiguity is analyzed as a conflict between several principles. For example, two grouping principles may lead to different and incompatible interpretations, in which case the intuition for grouping may remain vague or ambiguous. If the dance follows only one of these two principles, we expect this principle to override the other, so that the dance-music structure does not retain the ambiguity of the musical structure.[25] No such case arises in our case study, which, as we saw, does not involve any conflict between grouping principles.

But we observed two other types of ambiguity in group II of our case study, the main focus here. First, ambiguity can arise from underspecification: as we discussed (see Figure 9), the opening of

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[23] We could also switch perspective and explore what effects arise when structural aspects of the music match or mismatch the dance. It would be especially interesting in this respect to study a choreography danced to different types of music. This is for instance the case of Gallotta's piece *Ulysse*, which has been performed to various musical pieces over the years (1981, 1993, 1995, 2007). The Cunningham-Cage alliance in chance performances mentioned above in the text would also offer extensive testing ground for this.

[24] As suggested by an anonymous reviewer, this may have consequences for the perspectives of the choreographer and the dancer. For instance, it could be speculated that disambiguation of the accompanying music is a possible choreographic intention.

[25] We can further speculate that in case two grouping principles conflict in the music, but one overrides the other due to more intense application, the dance may reverse the effect in reinforcing the weaker grouping.

the Augurs of Spring is subject to be perceived as a four-level grouping structure due to the principle of parallelism applied to the repetition of the same chord throughout the first eight measures. But in the absence of any reinforcing local cue, it remains unclear to what extent this structure is actually perceived. The structure of the accompanying dance has the potential to specify at least some aspects of this structure. As we saw too (see Figure 15), the metrical structure of group II inherits this underspecification due to the global meter/grouping interaction rule and the absence of congruent local metrical cue – although the inherent temporal property of meter makes it likely that the previous passage serves as a guide, thus making more salient the lower levels of metrical structure (and thus grouping structure due to the meter/grouping interaction rule). Second, we observed that conflicts between local metrical cues (due to accents) and global considerations of metrical regularity and grouping/meter correspondence give rise to ambiguity leading to syncopation effects, as local cues are overridden by global constraints. We can assume that dance has the potential to strengthen or weaken such syncopation effects, thus stabilizing or destabilizing further the structure.

Both types of disambiguation are found in Béjart's and Nijinsky's group II. First, in Béjart's choreography, the regular jumps at the quarter note level strengthen the second metrical level – and thus the first (lowest) grouping level – of the music structure as indicated in Figure 28 (in red).

```
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|-------|-------|-------|-------|-------|-------|-------|-------|
|---------------|---------------|---------------|---------------|
|-------------------------------|-------------------------------|

x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x
x   x   x   x   x * x * x   x   x * x   x   x   x   x   x * x
x       x       x       x       x       x       x       x
x               x               x               x
x                               x
```

Figure 28 – Grouping and metrical structure of dance-music group II in Béjart's choreography

The strengthening of the second metrical level has several effects on the perception of the dance-music structure of this passage. First, it makes more salient this level, which I assumed to be only weakly perceived in the music. Second, it therefore makes the second grouping level more salient too, due to the grouping/meter interaction rule. Third, it weakens the syncopation effects (noted as asterisks in Figure 28) by stressing the strong beats and thus comparatively diminishing the musical accents on some of the weak beats. Fourth, it leads the observer to perceive the tactus at the quarter note level. Only based on the music, it indeed remains unclear whether the tactus is preferably perceived at the half note level (as suggested by the measure notation) or at the quarter note level. But remember that typically, the tactus is the level to which the observer spontaneously coordinates some movement (e.g. by taping their foot or finger). Béjart's choreography thus seems to incorporate such a movement (in fact, it seems difficult to tap one's foot at the half note level while watching Béjart's choreography) and thereby fix the tactus.

Nijinsky's choreography also stabilizes the perception of the structure in group II by disambiguating several aspects of it, but in a more complex way due to the richer structure of the choreography in this passage. First, due to the regular repetition of smaller and higher jumps, Nijinsky's choreography highlights the first and third levels of metrical structure as well as the second level of grouping (see Figures 22 and 24) as indicated in red in Figure 29.

```
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|-----------------------|-----------------------|-----------------------|-----------------------|
|-----------------------------------------------|-----------------------------------------------|

x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x
x   x   x   x   x * x * x   x   x * x   x   x   x   x   x * x
x       x       x       x       x       x       x       x
x               x               x               x
x                               x
```

Figure 29 – Grouping and metrical structure of dance-music group II under Nijinsky's choreography

Unlike Béjart's, Nijinsky's choreography thus leads us to perceive the tactus at the half note level. But like Béjart's, Nijinsky's choreography weakens the syncopation effects of the music by locally reinforcing the strong beats, thereby stabilizing the structure. The stabilization effect may be even stronger in Nijinsky's dance because it directly emphasizes the measure level both in grouping and

meter, and this level was already the predominant level in the previous musical passage, which as we saw, is likely to guide the perception of this passage.
That said, sharp arm movements of the dancers occurring on each musical accent conversely seem to strengthen these accents that are responsible for syncopation effects. But because arm movements tend to be perceived as secondary as compared to leg movements, I argue that these arm movements in fact indicate that the accents are secondary, thereby diminishing the syncopation effects and stabilizing the structure.

In sum, the dance-music rhythmical structure we perceive inherits the structure of both dance and music structures, and structural aspects that are indicated in both structures become more salient. This has the potential to disambiguate underspecified or ambivalent structures, as is the case in our case study where group II of the music involves underspecification and syncopation: in different ways, both Béjart's and Nijinsky's choreographies specify the structure by emphasizing some structural levels, and stabilize its perception by diminishing the syncopation effects.

3.2 Mismatch effects

In Béjart's and Nijinsky's choreographies, all aspects of the dance in group II match some aspect of the music, in the sense that all grouping and metrical levels induced by the dance can already be induced by the music at least to some degree. But it also often happens that some aspects of the dance do not have any counterpart in the music, as is the case of Bausch's choreography as we will see. What type of structure arises in such cases?
Results vary depending on the type of mismatch and the type of structure. First, grouping mismatch between dance and music can give rise to two main types of situation. In some cases, the dance may add some grouping level that is absent from, but does not conflict with the music. In this situation, we can hypothesize that the dance grouping is simply added to the musical grouping to create a richer dance-music grouping structure. In other cases, the dance may add some grouping structure that conflicts with the musical grouping. Such a situation can be assumed to be similar to a situation in which several grouping principles conflict within the music or within the dance alone. Depending on the type of grouping rule involved and depending on the intensity of each grouping effect, this situation can result in ambiguity or in some principle(s) overriding the other(s). I leave

the details for another occasion as neither situation arises in our case study, which does not involve any mismatch between dance and music grouping structures.

Mismatch in metrical structure differs from mismatch in grouping structure, I suggest, due to the modality effect on meter that we discussed earlier (see section 2.2). In a nutshell, given that metrical structure is more easily perceived in the auditory than in the visual modality, I hypothesize that in cases of conflict, the musical metrical structure usually overrides the dance metrical structure.

This is partially observed in Bausch's choreography. The rhythmical structure of Group II in this choreography partially matches the music structure, thus giving rise to the same type of stabilizing effect as Nijinsky's and Béjart's choreographies discussed above. Specifically, the weight shifts emphasize the second level of metrical structure, and the repetition of the same sequence of movements highlights the third level of grouping (Figure 20), as well as the fourth level of metrical structure due to the grouping/meter interaction rule, as shown in Figure 30.[26]

```
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|-----------------------|-----------------------|-----------------------|-----------------------|
|-----------------------------------------------|-----------------------------------------------|

x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x
x   x   x   x   x * x * x   x   x * x   x   x   x   x   x * x
x       x       x       x       x       x       x       x
x               x               x               x
x                               x
```

Figure 30 – Grouping and metrical structure of dance-music group II in Bausch's choreography (without taking into account arm and head movements)

[26] As noted by an anonymous reviewer, the first move of the dance (repeated four times) does not consist in a single weight shift as implied by the main text, but more precisely in a weight shift of the right foot followed by a weight shift into the left foot, which complexifies the dance-music structure. The reviewer takes these two weight shifts to occur on the first two eight notes respectively, so that the accent in the dance (with head bounce and weight shift into the left leg) would then match the first off-beat musical accent. But in fact, a very slow watching of the video confirms that the second weight shift (into the left leg) with head bounce occurs on the first 8th note, while the first weight shift (into the right leg) occurs before it. As noted by the handling editor, only one dancer (on the viewer's left) seems to be slightly delayed according to the reviewer's perception; but after checking another performance of the same choreography, I can confirm that this is not intentional, but a performance defect. I thus assume that it is the second weight shift (into the left foot) that is perceived as a strong beat (in fact, it is synchronized with the head bounce). I analyze the first weight shift (into the right foot), which is perceived as a preparatory move, as an anacrusis (i.e. the span from the beginning of a group to the strongest beat in the group, see Lerdahl and Jackendoff 1983: 30) both in the dance alone and in the dance-music event. This additional complexity does not affect the rest of the discussion.

But while these aspects of the movement match and disambiguate the music, other aspects – in particular arm and head movements – do not have any counterpart in the music and therefore complexify the dance-music rhythmical structure. As we discussed in section 2.2, they induce the application of local metrical rules that give rise to the metrical structure indicated in Figure 31 (repeating Figure 26); furthermore, I argued that even if these local rules conflict with global considerations of grouping/meter interaction (see Figure 25), this structure gradually becomes the preferred one (as the passage progresses) for the dance alone.

```
x  x  x  x  x  x  x  x  x  x  x  x  x  x  x  x
   x     x     x     x     x     x     x     x
         x           x           x           x
```

Figure 31 – Metrical structure of Bausch's dance group II induced by local rules

If we compare Figure 31 with Figure 30, we observe that the two higher levels of Figure 31 conflict with the higher levels of Figure 30, which are induced by the music (and the dance grouping structure due to the rule of meter/grouping interaction). Bausch's choreography thus exemplifies a case of conflict between the metrical structures of the music and the dance.

My intuitions about the perception of the dance-music structure of this passage lead me to conclude that the musical structure overrides the dance structure, thus creating syncopation effects on the beats marked as strong in the dance but weak in the music. The dance-music metrical structure therefore involves syncopation effects at all levels (excluding the highest level, which is only induced by the grouping/meter interaction rule under the assumption that the parallelism rule is recursively applied four times): while the music involves syncopation effects at the second metrical level, the dance adds syncopation effects at the third and fourth levels as shown in Figure 32 (using asterisks).[27] Unlike Nijinsky's and Béjart's choreographies, which induce stabilization effects, Bausch's choreography contributes to reinforcing the instability of the music.

[27] As noted by an anonymous reviewer, the syncopations induced by the dance furthermore precede the syncopations in the music, giving rise to a foreshadowing effect. A detailed analysis of this type of artistic effects goes beyond the scope of this article.

```
x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x
x   x   x   x   x * x * x   x   x * x   x   x   x   x   x * x
x   *   x   *   x   *   x   *   x   *   x   *   x   *   x   *
x           *   x           *   x           *   x           *
x                               x
```

Figure 32 – Metrical structure of dance-music group II in Bausch's choreography

Bausch's choreography thus illustrates how metrical mismatches between dance and music can complexify the dance-music structure perceived. It also shows how the metrical structure of music prevails over that of dance: the metrical structure of a dance-music event is primarily inferred from the metrical structure of the music in the sense that the perception of strong beats is preferably guided by the music; cues for metrical strength in dance are not ignored, but give rise to syncopation effects. This hypothesis is consistent with the results of psychological studies discussed in section 2.2, which show the precedence of the auditory modality for rhythm perception.

The hypothesis of a metrical dominance of music over dance would be worth further testing in future research using a broader set of existing and experimentally created examples.[28] In particular, we observed that in our case study, the metrical structure of dance does not only mismatch with the metrical structure of the music, but also with the grouping structure of dance, which aligns with the music. It would thus be interesting to study cases where both metrical and grouping structures in dance conflict with the musical structures. I predict that the metrical structure of music should also prevail in that case,[29] but the conflict in grouping may create more complex effects.

[28] Whether existing choreographies or constructed examples are used, many possible protocols could be created to test the perception of metrical structures in dance-music events. As mentioned in fn. 17, we could ask participants to propose a metrical structure themselves (e.g. by asking them to tap on what they perceive to be the beat, and forcing them to use different speeds of beats) or to rank various metrical structures (e.g. by asking them to rate different pairings of dance videos-artificial beats). We could also deduce the preferred metrical structure of participants indirectly, for instance by asking participants to perform other tasks at different positions of the structure, and evaluate their performance (e.g. reaction times to sound detection as in Lee et al. 2015). In any case, the stimuli should vary minimally with respect to their rhythmical structure as is standard in the linguistic methodology involving minimal pairs.

[29] At least if the metrical structure of music is sufficiently indicated: the hypothesis of a metrical dominance of music over dance does not exclude the possibility that the metrical structure of a dance-music event could sometimes be primarily inferred from the dance structure in cases in which the metrical structure would be much more clearly marked in the dance than in the music. A careful study of many more examples (based on existing choreographies or new experiments) would be necessary to specify the conditions that could make the metrical structure more salient in dance than in music.

In sum, general psychological results and our case study suggest that when we perceive dance and music together, we infer a single rhythmical structure to which dance and music contribute in a way that is partly affected by modality effects. The combination of dance and music grouping structures seems to follow the same rules as those used to combine several grouping principles within any cognitive system: match leads to reinforcement or disambiguation of the perceived structure, while mismatch gives rise to conflicts that can be resolved in several ways depending on the type and intensity of the grouping principles at stake. But the combination of dance and music metrical structures seems to be influenced by their modality difference: due to the dominance of the auditory modality for meter perception, music serves as primary guide for the metrical structure of a dance-music event, and conflicts with the metrical structure of dance give rise to syncopation effects.[30]

4 Conclusion

In this paper, I hope to have shown that it is productive to inquire into the human capacity of dance perception by using formal methods inspired by linguistics. By comparing the rhythmical properties of three dance pieces performed to the same music, I have argued that the grammar of dance can be treated in parallel with the grammar of music as proposed by Lerdahl and Jackendoff (1983): in particular, dance rhythm, like musical rhythm, can be analyzed as resulting from the interaction between grouping and meter preference principles.[31] It is especially significant to observe that dance also involves metrical structure, which, unlike grouping, is not common across cognitive systems. The structural similarity between dance and music led me to hypothesize that the perception by a viewer of dance and the perception by a listener of music are largely part of the same cognitive system.

But in parallel to sign and spoken languages with respect to the linguistic system, dance and music belong to the same abstract system though being perceived in different modalities. This modality

[30] We may speculate that this dominance of music for metrical structure may be partly responsible for the fact that dance is most of the time accompanied by music, while the reverse does not hold: the metrical structure of dance may require some auditory support.

[31] To further determine to what extent musical structures can be adapted to dance, it will be necessary to investigate the counterpart of pitch structure (time-span reduction and prolongational reduction, in Lerdahl and Jackendoff's 1983 terms) in dance. In particular, this will allow us to study headedness in groups and to specify how the notion of tension and relaxation can play a role in dance (see Lasher 1981, Krumhansl and Schenck 1997, Charnavel 2016).

difference affects not only the nature of the perceptual features relevant to the formulation of local grouping and metrical rules, but also the relative salience of metrical structure: metrical structure seems to be preferably and better perceived in the auditory modality than in the visual modality. Furthermore, the intrinsic link between dance and music led me to hypothesize that in a dance-music event, we perceive a single rhythmical structure that results from a combination of the musical and dance structures.[32] We examined match and mismatch effects, and concluded that modality also affects the way dance-music metrical structure is primarily inferred from music.

I discussed all these hypotheses and illustrated some of them on the basis of a detailed analysis of the opening of Stravinsky's *Augurs of Spring* as choreographed by Nijinsky, Béjart and Bausch. Many more detailed analyses will be required in order to further test and specify the hypotheses I made. In particular, it would be fruitful to study cases where instead of the music, the choreography was created first, and was accompanied by various musical pieces (see e.g. *Ulysse* by Gallotta, see fn. 23). It would also be interesting to study dance by deaf people. Several aspects of the hypotheses will furthermore require experimental testing: an experimental setting will allow us to systematically evaluate the perceptions of many observers and/or listeners, not only about existing dance and musical pieces, but also about new movement stimuli minimally constructed in the absence of artistic concerns.

Recall indeed that the goal of our exploration is not to analyze artistic effects. Nevertheless, it may be worth noting that determining the basic principles governing the understanding of dance and music should indirectly help us clarify some aspects of artistic questions. For instance, the detailed investigation of the rhythmical structure of our case study allowed us to specify some of its artistic effects. Stravinsky's music incorporates two contradictory tendencies in the opening of *the Augurs of Spring*: while the regular repetition of chords induces stability, the irregularity of accents induces instability. We showed how Bausch intensifies the latter aspect by further destabilizing the structure, while Nijinsky's and Béjart's choreographies intensify the former aspect by stabilizing it. In sum, inquiring into the human capacity for dance perception promises to shed further light on human cognition at several levels, not only by clarifying the distinction between

[32] To pursue the comparison with sign and spoken languages, it would be interesting to examine simultaneous combinations of sign and spoken languages (namely, code-mixing or mode-mixing, see e.g. Berent 2006) as well as combinations of spoken language and gestures. At first glance, it seems that mismatch is not found in mode mixing in the linguistic system, at least not to the same extent that it is found in dance-music events. This is probably due to the fact that the linguistic system is only based on well-formedness rules while the dance-music system also uses a preference rule formalism.

general cognitive capacities (like grouping) and domain-specific or modality-specific properties (like meter, to some extent), but also by providing a new angle to analyze artistic effects.

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Appendix: supplementary material

The videos on which this study is based are available on OSF at the following link:
https://osf.io/4erwa/

Captions:

Video 1: Musical excerpt under study from *the Rite of Spring* by Stravinsky (1913).
Music played by the Cleveland Orchestra conducted by Lorin Maazel.
With the official publisher's scores (revised in 1947).

Video 2: Vaslav Nijinsky's choreographic excerpt under study (1913).
Music played by the Orchestra of the Prague National Theater conducted by Allan Lewis.
Dance performed by the Joffrey Ballet in 1987.

Video 3: Maurice Béjart's choreographic excerpt under study (1970).
Music played by the Belgian National Orchestra conducted by André Vandernoot.
Dance performed by the Ballet of the Twentieth Century in 1970.

Video 4: Pina Bausch's choreographic excerpt under study (1975).
Music played by the Cleveland Orchestra conducted by Pierre Boulez.
Dance performed by the Wuppertal Opera Ballet in 1980.