Gesture - Music

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Abstract

In this article, we comment on various definitions of the term *gesture* in the general literature of human-human and human-computer interaction and in the musica domain.

Different propositions of gesture classifications are then discussed and topics from other disciplines, that are important to the discussion on gesture and music, are presented.

Concepts developed by the first author related to *instrumental gestures*, such as *energy continuum*, *gestural channel*, and *instrumental gesture typology* are reviewed in this context. The introduction of case studies on acoustic instruments helps in supporting the theory.

Finally, the role of non-obvious (*ancillary* or *accompanist*) gestures is discussed with respect to clarinet playing.

Introduction

What does one mean by "*gesture*"? In this article we carry out a survey of the general literature on human- human and human-computer interaction in order to devise basic characteristics defining a framework in which different interaction contexts occur.

We do so in the next section. It will become clear from the beginning that there will hardly be *one* common definition of gesture. Although we do not intend to provide a unique definition of *gesture* at the end of this survey, we believe that it is useful to compare the various definitions and point out the specificity of this topic in the musical domain, with respect to related communication fields.

General Discussion

The analysis of the definitions presented in appendices A and B shows different, even disparate, notions attached to the term gesture. Nevertheless, there is necessarily a common denominator that we will try to bring out by critically commenting on the definitions.[1]

Analysis Framework

Let us chose the definitions we will comment on by initially discarding dictionary definitions, provided for the sake of information. Let us also discard too focused ones, that only take into account the ordinary notion of "hand movement", or the opposed ones, such as B.2.a, that sees gesture only through the angle of physical technique. The same is valid for other definitions – pertinent but specific – used in specialized domains such as co-verbal gestures (A.2.b, A.2.a) and sign language (A.4.a). We will attach ourselves to the ones that, being more detailed, present some confusion or potentially prejudicial restrictions.

1. Let us not forget that these definitions have been taken out of their original contexts, and therefore do not fully represent their original meaning. Moreover, many of the quoted texts surely did not intent to propose a general and universal definition of the term "gesture", but only focus on a specific meaning in the context of the correspondent article.

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Free-movements or manipulation?

Definition A.3.a (and A.3.c) is elaborated and more modern than others in that it replaces the notions of *feeling, idea, emotion, intention, sentiment, attitude, passion, opinion* by the neutral and more contemporary concept of *information*. However, the idea of gesture is here reduced to what is perceptible to vision and during the time of its execution. Should one then consider as not gestural the movements of a violin player or of a graphic designer?

Writing

In the same article, writing is not considered as a gesture under the assumption that only the resulting words convey information. This is only the case of typewriting (and one could add: *in non real-time*!). Handwriting comprehends the realization of a drawing that itself contains an expression, an interesting information, indeed essential in the case of graphological studies.

Furthermore, the production of identifiable characters or of words is not absolutely separable from the graphical function in the case of handwriting or from the articulation/sequence of event characteristics in typewriting. The words produced do not contain traces of these characteristics, but these are essential to their realization.

Also important in *type*writing, as P. Viviani states, is to consider the personal timing style of the writer *since it marks the sequence of intervals with easily recognized "prosodic" traces*. Or, as researchers showed more than a century ago, telegraph operators could recognize the sender of a Morse code message only by means of temporal variations (modulations) in the Morse signal that are idiosyncratic to each operator [Viviani98]. This fact was later known as temporal homothety (Fr. homothétie), i.e., the motor system tends to impose a stereotyped temporal modulation to all discrete sequences of units of action.

The case of writing shows in fact that the nature of information – for both the gestural and other expression channels – is neither unique nor absolute. It depends on the object and on the observer's point of view. It also shows that the gestural behavior makes up a (complex) whole, a system made of multiple functions that articulate and combine among themselves. To excessively separate or divide it may mean loosing its substance.

Posture and Gesture

Definition A.2.a excludes whatever relates to *practical actions, postural adjustments, orientation changes, self-manipulations*. This allows us, by the negation, to characterize the term gesture. One needs however to remain prudent in the sense that, similarly to what was discussed before, one cannot strictly consider the significant part of a gesture, whatever it may be, independently from the postures that allow its correct execution.

The division of posture and gesture in definition A.4.b as respectively a *static form* and a *dynamic form* – the last as a sequence of static ones (similar to viewing a film frame by frame) can be criticized in the same manner. This separation may occult what, in the gestural behavior, is intrinsically a matter of the dynamics of movement.

The Role of Meaning

The majority of the gesture definitions cited above refer to the notions of expression of feeling (A.1.a, A.1.b), idea, emotion, intention (A.1.c), expression of — or emphasis on — an idea, sentiment, or attitude, sentiment () or passion, emphasis on an argument, assertion, or opinion (A.1.d) or information (A.3.a) and finally the notion of meaning (A.3.b, A.1.c). In this way, according to all these definitions, should one exclude from the domain of gestures those actions related to the execution of long acquired skills – by a cabinetmaker, a mason or a surgeon – that do not have an expressive function, but a material objective, and require a technique, know-how, experience, talent and intelligence?

The notion of *meaning – information that contributes to a specific goal to oneself or to a partner in communication* (A.3.b) – is more general than *feeling*, *emotion* and so on. It is enriched with the idea that the partner may be a human being or a machine (thus an object).

But this notion remains problematic in the sense that, not only because one can envisage to capture, sample, rationalize in finite digital data, the physical phenomena produced during the interaction between an individual and a material object on which one works (e.g. the molding of a cabinetmaker), it is possible to reduce skillful gestural actions to a transmission of information. In fact, the notion of partner is restrictive: in the case of the cabinetmaker, who is his partner? The piece of furniture! One could name the users of the furniture, who may admire its beauty; but in the case of the surgeon who performs a "surgical gesture"? When one elaborates an object such as a piece of furniture, one does not communicate – one

arranges, transforms, puts together the matter – and the object is not just information, but an ensemble or system of functions, and the gestures used for its creation are of a richness, a complexity, a specificity much bigger than to wave goodbye with one's hand.

Should one thus exclude the notion of gesture from these rich, complex and subtle actions of our members and our bodies, since they do not necessarily present an objective of information?

They do also produce something, in material conditions that may be quite similar and require from the individual the same categories of faculties and competencies.

And furthermore, the produced objects may *a posteriori* eventually become communicational objects, considered as containing information. Moreover, this information may be decoded by the addressees independently from what the original individual might have wanted, believed or had or not conscience of emitting.

Gesture in music

From the above analysis, the definitions from other fields seem hardly to adapt to the gesture in music.

Moving to the musical domain, definitions B.1.b and B.2.a tend to consider gestures as equivalent to physical (playing) techniques or performer actions. Although potentially restrictive as explained above, they overcome the notion of gesture as a hand sign where any (instrument) manipulation is excluded.

On the other hand, definitions B.3.a and B.4.a, are partially or completely concerned by the topic of *musical gestures*. One can see from these examples that the notion of *musical gesture* may be completely independent from the idea of gesture as an actual human movement, or as definition B.3.a states: *The notion of a musical gesture that at the time it occurs involves no actual human movement but merely refers to it is quite common*. This is seen from definition B.4.a.

One may also note that in B.3.a the notions of gesture and posture are mutually exclusive. As commented above, this separation of gesture and posture as two independent or even opposed notions is restrictive and does not correspond to the real situation where both co-exist (see below), although it may be useful in a purely dichotomous reasoning.

Finaly, let us analyze definition number B.1.a. The term "wave form" used there denotes a confusion between the object and the analysis (the different analysis levels or simply observation levels) of the object. The "wave form" (it would be more interesting to say the "signal") can be observed or analyzed with spectral analysis tools, Fourier, etc., but it may also be observed or analyzed by means of other formalisms permitting the identification of structures at a more elaborated level; the analysis tools in such a more elaborated level may use analysis results from a less elaborated one, but this need not necessarily always be Fourier analysis. The "musical gesture" would then correspond, depending on the point of view, to an ensemble of observable features between the level of elementary signal analysis and the lowest level of musical intention analysis.

Regarding the bi-directionality of the definition, there certainly exists a similarity in the abstraction level, but is this sufficient to justify the use of the "label" gesture in both cases? Moreover, what is the interest in employing the term gesture in the second case (from signal to musical intentions) if not only to indicate that the features being considered could be – without meaning that they eventually are – produced by a gesture in the first direction?

From the above exposed, two remarks can be made:

a) In the category of the features cited in B.1.a, there are phenomena that are not necessarily produced by gestures (in the first direction) – for instance, all natural movements such as flux (wind, water, sand, etc.), falls, crumbling, etc. – so why associate "gesture" to these phenomena, if not with an anthropomorphic intention?

b) Confusion is induced between *significative* and *signified*. It is not sufficient to recognize that "*The gestures that are fed to the instrument are of a physical nature (fingering, pressure, energy, etc.) whereas the gestures resulting from our auditory perception are not*." We consider that the word *gesture* (or the French equivalent *geste*) necessarily makes reference to a human being and to its body behavior – whether they be useful or not, significant or meaningless, expressive or inexpressive, conscious or not, intentional or automatic/reflex, completely controlled or not, applied or not to a physical object, effective or ineffective, or suggested.

Gesture – General Framework

From the above exposed, one can reasonably state that there cannot exist one single (*simple!*) definition of the term *gesture*. The multiple complementary definitions are tied up to their original context and therefore valid in their own right, although one must be aware of common traps such as simplistic dichotomous notions or too focused definitions, such as considering gesture in music as only a hand sign.

In essence, the *direct* or *indirect reference* to *human physical behavior* tends to be the common denominator to all the notions. However, it also seems important to make a distinction between *signifiant* and *signified*, or respectively gestures effectively produced and gestures evoked through listening, for instance.

Furthermore, it is important to explicit the description of basic properties and the characterization of each gesture, that eventually lead to subsequent gesture typologies tied to each specific context.

Analysis of different gestures

The main point of this article, as we already stated, is to discuss human-human and/or human-machine communication through gestures in a musical context. One may initially note that, when modeling this relationship, it is usual to progress from a pure description of the phenomenon (*phenomenological modeling*) to a comprehension of the original (causal) mechanism involved in the process (*structural modeling*). [Cadoz94b]

An attempt is proposed by Christophe Ramstein [Ramstein91] and consists in the analysis of instrumental gestures through three approaches:

- A *phenomenological* approach (a descriptive analysis);
- A *functional* approach;
- An *intrinsic* approach (from the musician's point of view).

The first (*phenomenological*) approach is based on three criteria: *cinematic, spatial and frequential.* The cinematic criterion consists in the analysis of the movement speed; the spatial criterion consists in the size of the space where the gesture takes place, for instance: large (arm movement) or small (finger movement). The frequential criterion takes into account movement decomposition regarding its frequential content, roughly between some tenths of a hertz to 10 Hz.

The second approach, *functional analysis*, refers to the possible functions a gesture may perform in a specific situation. It will be analyzed later in this paper with the introduction of the concept of instrumental gestures.

Finally, the third approach, *intrinsic analysis*, is based on the conditions of gesture production by the performer. It is a function of the perception of the different body affordances in a musical context, i.e. the hand as a means of fine action and perception due to its dexterity and number of nervous receptors, the feet as mostly suited to the performance of slower and more static movements, whilst other body parts have transport and/or accompanist roles, but also serve as the general support (stability) for the instrument. As a complement to the perception of body affordances by the player, one can also consider for instance the importance of the general relation to the player's environment [CLF81] [CLF84]. In order to analyze the diversity of trajectories and gestural behaviors of different actions within a system (fingers, hands, wrists, arms, etc.), three *action groups* have been proposed as a) Frontal action – moving away or towards a device; b) Vertical action – where gravity accentuates or opposes a gesture; and c) Lateral action – side to side movement.

In the next sections, a discussion of the first and second approaches is developed in detail.

Phenomenological Analysis

From the previous discussion on the different gesture definitions presented in the beginning of this article, one may notice the importance of understanding the basic physiological behavior of the human body when modeling the interaction between man and a machine. In order to situate the question, let us first quote a paragraph from an article, by Paolo Viviani [Viviani98], comparing the act of writing to that of speaking:

> "La situation est toute autre dans le cas de l'écriture [par rapport au langage]. Quelle que soit la manière d'écrire, nous employons essentiellement les mains, les doigts et des structures nerveu-

ses qui, non seulement, ont évolué dans d'autres buts, mais surtout, n'ont pas subi des modifications adaptatives pour assumer cette nouvelle tâche. Ceci a un côté positif, nous laissant une grande souplesse dans le choix des techniques d'écriture — du stylus acadien au clavier des ordinateurs — mais aussi un côté négatif : nous ne le connaissons que trop bien pour avoir passé les plus belles années de notre enfance à apprendre à écrire.
Justement, toute la difficulté de la tâche [écriture] tient au fait de devoir utiliser les moyens de bord — les capacités génériques du système moteur — pour maîtriser un code gestuel aussi arbitraire que celui employé pour jouer de la harpe...[2]"

As we have already stated, we are here precisely interested in the case of playing an instrument. This means that the study of gestures (in the broad sense) could hardly be dissociated from the study of the human motor system's properties, both at the level of its physical behavior and of its cognitive processes.

Let us therefore review some concepts related to the production of gestures from other domains.

Muscular activity: Motor Units

Motor units are the basic functional elements of muscular activity. They can be classified according to force produced and to the speed of contraction and relaxation in *slow* or *fast units* [BGRS94].

- *Slow motor units* have a limited contraction speed, produce a small effort and are less sensitive to fatigue. They are present for instance in postural muscles, which are able to produce small efforts for extended time.
- *Fast motor units*, on the other hand are able to contract/relax quickly producing a significant effort, but being more sensitive to fatigue.

It is interesting to notice that intermediate cases exist and that some muscular fibers can change their categories in response to physical exercises.

Basic types of movement

In the analysis of motor behavior [BGRS94], it is common to oppose human movements as *slow movements*, that mainly present problems of regulation, such as the equilibrium, manual grasp, and manipulation and *fast movements*, where anticipation constraints dominate, such as jumps, throws, and strikes. The same idea is sometimes expressed [Goldstein98] in terms of "*Current control*" – sustained movements that can be controlled while they are performed and "*Ballistic control*" – short and energetic movements.

A complete description of the characteristics of movement can be found in specialized texts, such as [Massion97]. It will be summarized here in order to give an idea of the different types of human movements, the reader being referred to the original text for a complete discussion.

The first distinction is related to the origin of the movement being performed: *passive* and *active* movement.

Another distinction relates to the *nature of the movement* performed, resulting in:

- Reflex movements;
- Automatic movements;
- Intentional movements, that can be either:
  - triggered or
  - auto-initialized.

Analyzing *intentional movements*, Massion devises the following movement types:

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2. The situation is completely different in the case of writing [compared to that of speaking]. Independently from the type of writing, we essentially use the hands, fingers and nervous structures that, not only have evolved for other goals, but mainly have not suffered adaptive modifications in order to assure this new task. This fact has a positive point: it gives us the facility of choosing the writing technique — from the Acadian stylus to computer keyboards — but also a negative one: we know extremely well what it means to spend the most beautiful years of our childhood learning to write.
All the difficulty of the task comes from the fact of being forced to use the available means — the generic capacities of the motor system — in order to master a gestural code as arbitrary as the one used to play the harp. [Translated by the authors]

- Simple or complex (mono or pluri-articular);
- Discrete (one element or one sequence of elements) or rhythmic;
- Slow or fast;
- With or without a defined goal;
- With or without feedback;
- Isometric (in order to produce a force) or Isotonic (in order to produce a displacement).

Finally, the same differentiation expressed above as *slow/fast* or *current/ballistic* movements, may also be proposed as three types:

- Pure ballistic movements,
- Rapid movements with "breaking" and final adjustment,
- Slow movements.

Gesture and posture

Posture and gesture *co-occur*. According to [BGRS94, p. 603], "*The coordination between posture and movement condition the efficiency of the gesture. In fact, postural muscular activities, static or dynamical, anticipate, accompany and follow the execution of the movement in an automatic manner*" and later in the same page: "*... What is seen as just a static form is the result of a dynamical process [...] One recognizes in the form of the muscles the fixed representation of the forces they deploy*".

Gesture production

As A. Riehle points out [Riehle98], the research on cognitive psychology has allowed the identification of three operation phases of the central nervous system with respect to motor behavior: a) selection of response that best adapts to the situation from a repertoire of possible responses; b) definition of the characteristics of the selected response; and c) execution of the movement. This last one is at the origin of the activation of muscular command, responsible for the observable mechanics of gesture.

Coming back to the research originally developed on writing [Viviani94], another interesting physiological aspect of gestures is that of the *motor equivalence principle*: the form (geometrical relations) of a gesture is preserved independently from the articulations and muscular groups that generate it. This means that, even before being formulated as a sequence of muscular commands, the intention of writing gives place to an abstract representation of the desired form, in its metrical and topological relations. Stated another way, this principle suggests that the motor system codes the formal aspects of the gesture in a register separate from that where the muscular synergies are specified.

This is made explicit by the notion of *motor program*, defined by Viviani as:

> "Il s'agit d'une structure abstraite, stockée dans le cortex, correspondant à un geste particulier, qui spécifie les rapports topologiques et séquentiels entre ses composantes ; une fois sélectionnée, cette structure engendre une séquence de commandes dont l'ordre préétabli n'est pas modifiable par les afférences sensorielles. Les déterminants métriques et temporels du geste, ainsi que les groupes musculaires impliqués dans son exécution, ne sont pas spécifiés explicitement par le programme. Celui-ci prévoit un ensemble de paramètres qualitatifs et quantitatifs qui, fixés au moment de l'exécution, déterminent les aspects spatio-temporels du geste et les synergies musculaires nécessaires, la fixation des paramètres étant assurée par des processus indépendants du programme." [Viviani94, p. 785][3].

3. " It is an abstract structure, stored in the cortex, corresponding to a specific gesture, that specifies the topological and sequential relations between its components; once selected, this structure generates a sequence of commands which pre-established order is not modifiable by sensory information. The metrical and temporal determinants of the gesture, as well as the muscular groups implied in its execution, are not explicitly specified by the program. It just foresees a group of qualitative and quantitative parameters that, fixed at the time of execution, determine the spatio-temporal aspects of the gesture and the necessary muscular synergies, the fixation of the parameters being assured by processes independent from the program." [Translated by the authors]

Another aspect of human movements shown by the research in experimental psychology is the relation between the speed and the curvature of a movement's trajectory: the bigger the curvature the slower the speed [Viviani94]. This can be seen, for instance, in the case of conducting gestures, where the baton moves faster in straight lines than in curved trajectories. This natural kinetic modulation would have its origin in the neural mechanisms commanding the movement, and not in the muscles themselves [Reyraud98].

Finally, let us cite another property of human movements, that of *isochrony* [Viviani94]. It states that, in the absence of an explicit temporal constraint, the mean speed of a gesture is related to the length of the its trajectory. This means that the same gesture executed in different scales (e.g. paper or blackboard) would take approximately the same time to be completed [Berthoz97].

Gestural Primitives

A natural sequence of what has been exposed so far about the physiological properties of movement would be to define basic movement characteristics in a musical context by means of their primary properties, without any higher level analysis of them – such as gesture meaning or function, for instance.

This point of view may be very well suited to the case of *non-traditional* human-machine interaction in music (man-musical instrument), such as the case of sound installations or virtual reality settings, where gesture functions may be hard to define or even meaningless.

According to Insook Choi [Choi98][4], Gestural Primitives are "fundamental human movements that relate the human subject to dynamic responses in an environment". The author proposes three types of gestural primitives, both device- and signal-independent:

- Trajectory-based primitives: e.g. changes of orientation;
- Force-based primitives: e.g. gradient movements;
- Pattern-based primitives: e.g. quasi-periodic movements.

Those three types are considered as having *dominant* (but *not mutually exclusive*) movement properties. Furthermore, each of the above primitives may "embed other movements, while they distinguish the primary intention of a performer."

Functional Analysis

Moving to another level, one could analyze gestures based on a purely functional approach. This area has been extensively researched, but as shown in the previous sections of this paper, there are many different (divergent) directions when it comes to the musical context[5].

We will here speak generally about the gestures of an instrumentalist playing his instrument, as F. Delalande has proposed in [Delalande88], then focus on the effective gestures used to play an instrument, or *instrumental gestures* [Cadoz88], and finally shortly discuss ancillary gestures specifically in the case of the clarinet playing technique. Ancillary gestures, although not produced intentionally in order to generate or modulate sound, are present and part of top-level performers.

Three Level Gesture Classification:

In an interesting study on the playing technique of the late pianist Glenn Gould, François Delalande [Delalande88] proposed a division of the notion of gesture in three levels, "*from purely functional to purely symbolic*":

Effective gesture - necessary to mechanically produce the sound - *bow*, *blow*, *press a key*, etc.

Accompanist gesture - body movements associated to effective gestures - chest, elbow movements, mimics, breathing for a piano player, etc.

Delalande suggests that accompanist gestures should not be analyzed strictly from a motor control point of view — he considers that its function is as related to imagination as to the effective production of the sound.

4. See Choi's article on gestural primitives in this volume.
5. Again, we stress that this approach is tied to the case of *instrument* playing, and would not necessarily make sense when applied to other types of gestural interaction.

Figurative gesture - perceived by the audience but without a clear correspondence to a physical movement - a melodic balance, etc.

The first two proposed levels correspond to physical actions of the instrumentalist, whilst the third is completely symbolic.

In this article we are mostly interested in the physical actions of the player and therefore we will not consider the third level. Furthermore, we'll concentrate on the first level and quickly comment on accompanist gestures, mostly in the case of the clarinet playing technique. In order to do so, let us study in detail the first level proposed by Delalande, in the light of the theory on instrumental gestures, developed by the first author and collaborators [Gibet97] [Cadoz88] [Cadoz/Ramstein91] [Ramstein91] [Cadoz94a] [Cadoz99].

Instrumental Gesture

Considering the context of traditional musical instruments, two facts can be initially remarked: 1) the need for instrument stability during the performance and 2) the existence of an energy continuum between the gesture and the perceived phenomena.

We will consider "instrumental gesture" as a subgroup of F. Delalande's three-tier gesture classification (*effective gesture*), i.e. the actual instrument manipulation and playing technique. Another characteristic specific to instrumental gesture is that it is produced by the "gestural channel".

Gestural Channel

The *gestural channel* is unique if compared to other human communication channels (visual, auditory, and vocal) in that it is both a means of action on the physical world *and* a means of communication of information. In this second role, the gestural channel has a double direction — *emission* and *reception* of information. It is therefore impossible to dissociate *action* from *perception*.

Stated another way, the gestural channel is specific in the sense that it is *twice double* [Cadoz94a]: 1) it allows *both* communicative and interactive relations and 2) it allows *simultaneous* emission and reception of information.

Considering the gestural channel, one can identify [Cadoz94a] three different functions associated with it, but that are nevertheless complementary and dependent on each other:

- material action, modification and transformation of the environment — the *ergotic* function;
- perception of the environment — the *epistemic* function;
- communication of information towards the environment — the *semiotic* function.

Let us analyze these functions by using the example of the hand — the primary organ associated to the gestural channel.

In the first function, *ergotic*, there is no communication of information but only energy communication between the hand and the object. Forces applied to the object cause deformation and displacement and part of the applied energy is fed back to the gestural channel.

The *ergotic* function is the one that allows the differentiation between communicative and interactive goals of the gesture.

The second function, *epistemic*, is typically performed by our capacity of touch and muscular/ articulatory sensitivity. This function is always related to the first (*ergotic*), in the sense that we need to be in contact with an object.[6]

It is important to remember that the simple cutaneous tactile perception (touch) is just one part of the epistemic function. Actually, the epistemic function is based on both the cutaneous and muscular perceptions [Roll94].

Finally, the third function, *semiotic*, is that of meaning, of communicative intent. It's the gestural function *per se* — actually, that is the only function associated to gesture in the sense of *free-* or *empty-handed* gestures — sign-language, natural gesture, gesticulation, pantomime, etc. It may also be present with the other two functions, for instance in instrument manipulation, where all three functions are interdependent.

6. Note that we're not considering temperature sensitivity.

It is useful to remark again that the three functions presented above as separate and mutually exclusive are in fact inter-dependent in reality. This inter-dependency of the three functions is, as we've already cited above, what characterizes the gestural channel, and particularly one of its modalities, the *instrumental gesture*. Furthermore, in the instrumental situation all communication channels can be simultaneously requested, contrary to other communication situations.

Instrumental gesture is considered as a "*communication modality"* complementary to empty-handed gestures. They are therefore singular in that they posses, *à la fois*, all three characteristics of the gestural channel: *ergotic*, *epistemic* and *semiotic*. One can use here the notion of *interactive* gesture as opposed to *unidirectional* gesture (exclusively semiotic).

One can observe this singularity by considering instrumental gestures associated to the production of music. Analyzing the diversity of musical instruments in detail, a number of possibilities for converting (instrumental) gestures into musical information come to mind.

Instrumental gestures are therefore intrinsically *semiotic*, in the sense that they address the listeners' ears and that one can judge the information being conveyed (sound). But, except for a very reduced number of instruments where no physical contact with the instrument takes place (as the theremin, for instance), instrumental gesture is also *ergotic* – the hands (or lips, feet, etc.) are in direct contact with the instrument by means of manipulation, displacement, percussion, and so on. There is energy being transferred to the object (instrument) and from the object as a reaction. Finally, one can then consider instrumental gestures as *epistemic*, since musicians use their tactile-kinesthetic perception in order to play an instrument. Let us now consider different situations in human-instrument interaction.

Instrumental Gestures - definition

Instrumental gesture is defined as a modality specific to the gestural channel, complementary to empty-handed gestures *("geste à nu*") and characterized as follows:

- It is applied to a material object and there exists physical interaction with it;
- In this physical interaction, specific (physical) phenomena are produced, whose forms and dynamic evolution can be mastered by the subject;
- These phenomena may then become the support for communicational messages and/or be the basis for the production of a material action.

Based on this definition, let's analyze some different types of gestures and place them in comparison to instrumental gestures:

- *Empty-handed gestures* are not *instrumental*, since they only posses one of the three functions of the gestural channel, the *semiotic* function. The same holds true for *conductor gestures*, since even if they may consist of a manipulation of an object (the baton), there is no direct energy transfer between the conductor and the listener;
- *Writing* or *drawing* are instrumental gestures, making use of objects (tools) in order to convey information. The tool in this case is therefore a conditioning agent for those gestures, determining the nature of the information conveyed by the user (a combination of the tool's properties and the user's intentions).

Let us now analyze instrumental gestures based on a typology according to their function (functional analysis) with respect to the instrument.[7]

Instrumental Gesture Typology

Based on the above considerations, the first author proposed [Cadoz88] a classification of instrumental gesture based on its function as:

- *Excitation* gesture;

7. Note only that it is important to keep in mind that the objective of the typology is to provide a *pedagogical* tool for the comprehension of the instrumental gesture phenomena as well as an *aid for the design* of gestural controllers. It should be obvious that, in the real situation, the proposed instrumental gesture categories are neither exclusive nor independent. In fact, as we are going to see later in this article, in many cases one action may present two or more of the proposed functions to different degrees.

• *Modification* gesture;

• *Selection* gesture.

Let's analyze these functions in more detail:

Excitation gesture is the one that provides the energy that will eventually be present in the perceived phenomena. It may be either:

• *instantaneous* (percussive or picking). The sound starts when the gesture finishes.

One can differentiate between picking and striking, since the gestural processes in these cases are different [Cadoz99]. In the first case, the vibrating structure is displaced from its initial rest position and when left to itself it starts to vibrate, i.e. there exists a silent contact phase. In the second case the structure starts vibrating straight after the initial (usually short duration) contact.

• *continuous*, when both the gesture and the sound co-exist.

A distinction can be made between a *continuous* gesture that produces a *continuous* excitation and a *continuous* gesture that, applied to specific objects, produces a *sequence of discrete excitations* [Cadoz99].

Modification gesture is related to the modification of the instrument's properties, without any substantial expense of energy being transferred to the final sound. This modification affects the relation between the excitation gesture and the sound and therefore introduces another expressive dimension. As the first author points out [Cadoz94a], modification gestures are determining elements with respect to the form, structure and function of the information phenomena produced.

Modification gestures may be either:

• *parametric* (or continuous), when there's a continuous variation of a parameter, such as vibrato, for instance. It can be either continuous or discrete (for instance in a violin or a guitar, respectively);

• *structural*, when the modification is related to categorical differences, such as the insertion/ removal of an extra part (a mute in the case of the trumpet, or a register in an organ).

Selection gesture is the one that consists of a choice among multiple similar elements in an instrument. One can consider two possibilities: either *sequential* or *parallel selection*. This gesture differs from the previous ones (excitation and modification) in that it neither provides energy to the resulting sound nor modification of any of the instrument's properties.

The *excitation*, *modification* and *selection* gestures make up the basis of the instrumental gesture typology. They represent general functions present in instrument manipulation techniques that may be found in different instrumental situations. The first author [Cadoz94a] even suggests a parallel between these elements and those of a language (noun, verb and adjective): excitation gestures would be related to the verb, modification gestures to the adjective, and selection gestures to the noun. In a complex instrument, instrumental gestures build up phrases where these three elements combine, sometimes in a very subtle way.

We next apply this typology to real-world instruments in a series of case studies.

Case Studies

By analyzing the expert interaction of players and acoustical instruments, we may gain an insight into the advantages and limitations of the proposed typology of instrumental gestures. We will here consider the case of three traditional acoustic instruments: the cello, the bagpipe and the clarinet.

Case study 1: The Cello

In a first analysis, one could consider, in the case of traditional bowing techniques:[8] [9]

• Right hand (bow) movement is an exciter gesture;

• Left hand linear movement is a parametric modification gesture; left hand rotation movement is a selection gesture.

8. For an analysis of the bowing techniques in a cello from an ergonomic point of view, the reader is directed to [Isart99].

9. See article by Serafin and Dudas in this volume.

Considering it in more detail, the right hand also performs a selection by means of hand rotation of the string to be excited. Also, the excitation gesture presents many degrees of freedom: the force applied, the amount of bow hair in contact with the string, the arm linear excursion, etc.

For both the right hand, for excitation and string selection, and the left hand, for modification (choice of a string length) and string selection, different instrumental gestures collaborate to a single musical functionality. This fact illustrates the complementarity of the instrumental gesture categories in real-life instrumental situations.

It is interesting to note that the dimensions of the instrumental gesture space do not always present an isomorphic relation to those of the perceptive space, i.e., one type of instrumental gesture (such as parametric modification) does not necessarily match one perceptive parameter (such as pitch).

Case study 2: The Clarinet and a MIDI Wind Controller

As another example of the instrumental gesture's typology, let's discuss a first-order model of a saxophone/clarinet, where one gesture accounts for one musical function. Considering each available output variable from a Yamaha WX7[10]:

- Breath pressure - *excitation gesture*;
- Lip pressure - *parametric modification gesture*;
- Key value (fingering) - *selection gesture*.

This description applies to a controller, that outputs three *independent* MIDI data streams. Let's now analyse a real clarinet:

- *Breath pressure* is an *exciter gesture*, sustaining the air column vibration, but *also controlling amplitude vibrato*, and can therefore be considered to a certain extent as a *parametric modification gesture*.
- *Lip pressure (embouchure)* is a *parametric modification gesture*, since it affects the instrument's pitch (frequency vibrato), *but also defines the excursion of the resulting loudness output*. It will control frequency vibrato and also timbral/amplitude changes.
- *Fingering* is a *selection gesture*, where the performer chooses specific keys for selecting a pitch (note), but it is well known that glissandi can be produced by partially opening the holes. We could then consider these gestures also as *parametric modification gestures*.
- *Changing the size of the instrument's tube* is a structural modulation gesture - as done in order to tune the clarinet before performance.

In an acoustic single-reed instrument, it is known that the air flow through the reed is dependent on the difference between the pressure inside the mouth and the pressure inside the mouthpiece, for a certain embouchure value [Benade90] [RWDD97]. In the case of a tight embouchure, even a great variation of breath pressure will not produce a comparable timbral nor loudness variation. What will probably happen in the case of strong blowing is a clamping of the reed and therefore the stopping of sound production, or a squeal. In order to produce a large excursion on timbral and loudness values, one should keep embouchure values low. *Consequently, it affects the way the exciter gesture works*. Breath pressure (considered as resulting from the difference in pressure described above, in the case of a MIDI wind controller) is thus related to a particular embouchure value. These two gestures are inter-dependent in a reed instrument.

Case study 3: The Bagpipe

The same analysis could be made for the bagpipe: blowing is a *biasing* gesture since it makes available the air that will eventually be forced through the reed from arm pressure on the bag. One could then classify this pressure as the exciter gesture, but the blowing would be a gesture that provides the initial state for the system.

10. Disregarding variables not related to the acoustical instrument behavior, e.g. the modulation wheel.

Biasing Function

Depending on the acoustic instrument analyzed, one can consider another gestural function, that *of reaching and continously maintaining a part of the instrument in an operation point*. More specifically, in the case of the clarinet, as seen above, one needs to keep the embouchure in a certain range in order to produce any sound at all (at least in order to produce oscillation).

This means that embouchure, in the case of a reed instrument, is *always necessary* to the instrument's traditional behavior and that it alters the effect of other gestures (blowing, for instance) in a non-linear way. Although strictly consisting of a parametric modification gesture, its function in this case could not be reduced to just the modification of the instrument's properties without taking into account its absolute necessity.

This extra gestural function, *biasing* gesture, is then complementary to the previous functions in the specific case of some acoustic instruments.

The need for gesture typologies

One can conclude that for a real instrument, it is not always simple to classify gestures according to independent functions, since they may be interrelated, and so it does not seem possible to separate gestures into different independent classes for all existing instruments.

The importance of gesture typologies is then not to completely describe acoustic musical instruments but to provide general guidelines for the design of gestural input devices, mostly regarding the presence of different types of feedback related to different gestures.

Examples of the use of such typologies are the pioneering Retroactive Gestural Transducers (TGR – transducteur gestuel rétroactif) developed at ACROE in Grenoble by J.-L. Florens and collaborators from 1978 onwards [Florens78] [CLF81].

Video available in the original CD-Rom version. Excerpt from *Le geste et l'outil*, an ACROE production (1990), realized by Alain Bos. Texts by Annie Luciani.

Accompanist Gestures

After having analyzed what Delalande [Delalande88] has called *effective* gestures, let us now discuss another type of (wind) instrumentalist's gestures, this time not primarily produced in order to generate sound. Delalande has called them *accompanist* gestures.

The second author has studied the gestural vocabulary of clarinet players, specifically gestures such as moving the instrument whilst playing. These gestures have been called *non-obvious* or *ancillary* gestures [Wanderley99a].

Although this study still consists in a work in progress, some preliminary results tend to show that some of these movements seem to present patterns that are consistently repeated by the player in different circumstances (i.e. rehearsals or concerts).

The Analysis of Video Recordings

In order to study ancillary gestures, we have undertaken the analysis of existing video recordings of concerts and rehearsals by different players:

- A video of clarinetist Alain Damiens playing Pierre Boulez's piece *Domaines*, in 1985.[11]
- A video of Marc Battier's[12] clarinet piece *Mixed Media*[13], recorded in 1993.

11. I would like to thank the copyright owners who kindly agreed on the usage of this video for this research.
12. Thanks to Marc Battier for providing the film.
13. Unfortunately, the name of the player could not be found.

• A video of clarinetist Jean-Guy Boisvert performing three pieces for clarinet and electronics, at Pollack Hall, McGill University on May 18, 1999.[14]

• *Ektenes III*, by Alcides Lanza

• *Eschroadepipel*, by Zack Settel

• *Praescio IV*, by Bruce Pennycook

The following figures show six shots of the first video recording. The total time of the sequence of figures corresponds to less than one second. One can note the upward movement of the instrument.

Fig. 1. A. Damiens playing *Domaines*, by Pierre Boulez, at Ircam in 1985.

Detailed Analysis

An analysis of the three videos reveals certain gestural patterns. As will be seen later in detail, some patterns seem to be produced by different players, whilst others seem to be rather idiosyncratic.[15]

A. Damiens playing Domaines

Considering the first video in detail, there are mainly three movements occurring at specific moments:

• Changes in posture at the beginning and during phrases.

• Slow continuous gestures, usually in an upward direction during long sustained notes, generally increasing in amplitude with an increase in the note's dynamics, sometimes presenting circular patterns.

• Fast sweeping movements of the bell that mainly accompany short *staccato* notes.

As seen in a later section, the movements seemed to correlate to the musical section actually played. This can be seen from the comparison of the same section played during warm up and during rehearsal (see below).

14. Thanks to Philippe Depalle for the video recording, and to J.-G. Boisvert for his kind agreement on the usage of these videos.

15. Much of the following results are drawn from [Wanderley99a] and from the second author's PhD thesis (to appear).

Mixed Media Performance

Analyzing the data from the second clarinet player, it can be seen that continuous movements may also be found in sustained notes. Nevertheless, not many fast gestures were found in the second video, but changes in posture seemed to be more frequent.

The next three shots show a sequence of movements taken from the video. One can note the posture differences between the shots.

Fig. 2. *Mixed Media* performance in Japan, 1993.

Recordings of J.-G. Boisvert

The third player (J. -G. Boisvert) performs different gestures, both round/upwards gestures during sustained notes and also sweeping fast gestures, as opposed to the second player. Posture differences were also noticed.

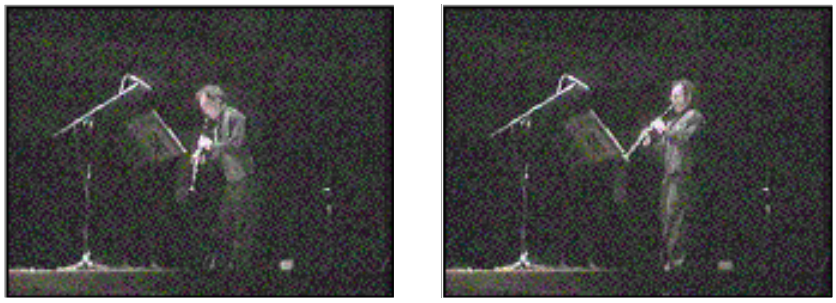

Fig. 3. J.-G. Boisvert playing *Ektenes III*, by Alcides Lanza, in Montréal, 1999.

Furthermore, the third of the pieces played by Mr. Boisvert is performed with the clarinet player *seated*. This is an interesting point considering that one could wonder whether whilst seated, a clarinet player would tend to move or not.

The following sequence of 6 shots shows a 5-second movement – note the differences in posture and the position of the instrument with respect to the microphone.

Fig. 4. J.-G. Boisvert playing *Praescio IV*, by Bruce Pennycook, in Montréal, 1999.

Repetition of Equivalent Movement Patterns

As could be expected, there seems to exist a correlation between the melody played and the movements performed. As an example, two phrases repeated twice in the first film – in the introductory credits and later during the piece *Cahier D, original* – are shown in the next figure. Note the tendency to reproduce the bell up movement in the two sequences of shots.

Fig. 5. A. Damiens playing Domaines, by P. Boulez, at Ircam, 1985. The first two shots (above) show a melody played during the warm up (introductory

credits of the film). The second two shots (below) show the same melody played during the performance.

Goals of this research

The main interest of this research is twofold:[16]

- The first point of interest is the understanding of why these gestures take place and whether there can be repeatable patterns across different players. Furthermore, other points are also important, among others:
  - What is the exact influence of the player's technical level (*beginner, semi-professional, professional*) and of the context (concert, rehearsal, audience size, etc.)?
  - The correlation of certain gestures to breathing?
  - Is there a correspondence between these gestures and other gestures humans make, for instance, whilst speaking?
- The second point of interest of this approach consists in the fact that, depending on recording conditions – specifically for close microphone positions — these types of gestures may influence the sound obtained in the recording [Wanderley99b]. A model of this influence can then be used as part of a virtual model of a clarinet.

Conclusions

This article presented a review of different concepts associated with the word gesture, both in the general literature on human-computer and human-human interaction and in the musical domain.

We have seen that there is a massive corpus of research on gestures, but this corpus of research should be carefully examined and adapted in order to be used in the musical domain, due to the idiosyncrasies of each field. We have purposely avoided providing another definition of gesture. Instead, from all the given definitions, we tried to point out their basic features and to stress the context in which they belong.

Comments on various gesture classifications were provided, both phenomenological and functional classifications, and examples of both gesture classification types in a musical context were presented.

We have also reviewed many related points from other disciplines such as physiology and experimental psychology, a summary of information that may prove helpful if someone is to understand the basics of gesture production by a human-performer.

A functional classification of gestures in an instrumental performance context have been reviewed, particularly a complete description of the first author's work on instrumental gestures. The theory on instrumental gestures has been illustrated by the introduction of case studies confirming and/or challenging it.

Finally, a discussion on accompanist performer gestures has been introduced and examples of clarinet performances discussed.

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16. Let us again make clear that we do not intend throughout this research to express *any* judgement about the playing technique of the different clarinet players. Our intention is merely to try to understand the mechanism of gesture production by the players and the correlation to other studies on gesture.

Appendix A
Review of General Definitions of Gesture

1- Dictionary Definitions

A.1.a

The Chancellor Illustrated Family Encyclopedic Dictionary, Oxford University Press, 1975.

gesture *n*. I. Significant movement of limb or body; use of such movements as expression of feeling or rhetorical device. 2. (after Fr. *geste*) Step or move calculated to evoke response from another or convey (esp. Friendly) intention. *~v*. Gesticulate.
gesticulate *v*. Use expressive motion of limbs or body with or instead of speech ; express thus.

Back

A.1.b

The Shorter Oxford English Dictionary, Oxford University Press, 1973.

gesture M.E. **2**. posture, attitude, *esp* in prayer or worship; **3**.b. Now only: movement of the body or limbs as an expression of feeling; **4**. A movement of the body or any part of it; now only as expressive of thought or feeling.

A.1.c

The Scribner-Bantam English Dictionary, 1979 Bantam Books Inc.

gesture [**ML** *gestura* posture, bearing] *n* **1** bodily movement expressing or emphasizing an idea or emotion ; **2** act conveying intention. ... SYN *n* attitude, action, posture, gesticulation.

A.1.d

WWWebster Dictionary, at: http://www.m-w.com.

Main Entry: **1 ges·ture.** Pronunciation: 'jes-ch&r, 'jesh- Function: noun
Etymology: Middle Eng., from Medieval Latin gestura mode of action, from Latin gestus, past participle of gerere
Date: 15th century
1 : archaic : CARRIAGE, BEARING
2 : a movement usually of the body or limbs that expresses or emphasizes an idea, sentiment, or attitude
3 : the use of motions of the limbs or body as a means of expression
4 : something said or done by way of formality or courtesy, as a symbol or token, or for its effect on the attitudes of others <a political gesture to draw popular support — V. L. Parrington>

A.1.e

Webster's Revised Unabridged Dictionary (1913).

Gesture \Ges"ture\, n. [LL. gestura mode of action, fr. L. gerere, gestum, to bear, behave, perform, act. See Gest a deed.]
1. Manner of carrying the body; position of the body or limbs; posture.
2. A motion of the body or limbs expressive of sentiment or passion; any action or posture intended to express an idea or a passion, or to enforce or emphasize an argument, assertion, or opinion.

2- Gestures and Speech

A.2.a

A. Kendon. 1996. "An Agenda for Gesture Studies." In *Semiotic Review of Books*. Home Page: http://

www.chass.utoronto.ca/epc/srb/srb/gesture.html.

> This 'strand' of activity (which we also refer to when we use the term 'gesture' or 'gesticulation') has certain characteristics which distinguish it from other kinds of activity (such as practical actions, postural adjustments, orientation changes, self-manipulations, and so forth). [17]

A.2.b

J. Cassell. 1998. "A Framework for Gesture Generation and Interpretation." In *Computer Vision in Human-Machine Interaction*, R. Cipolla and A. Pentland, eds. Cambridge (UK): Cambridge University Press.

> I am addressing in this paper one very particular use of the term "gesture" — that is, hand gestures that co-occur with spoken language.

3- Gesture in HCI

A.3.a

G. Kurtenbach and E. A. Hulteen. 1990. "Gestures in Human-Computer Interaction." In B. Laurel (ed.): *The Art of Human-Computer Interaction*, Reading, Mass.: Addison-Wesley, page 310

> A gesture is a motion of the body that contains information.
> Waving goodbye is a gesture. Pressing a key on a keyboard is not a gesture because the motion of a finger on its way to hitting the key is neither observed nor significant. All that matters is which key was pressed.
> Using your hand to show the motion of a falling leaf is a gesture. A teenager flailing at a video game joystick is not gesturing but rather is operating a controller that senses in which of eight possible directions a stick is being pushed.
> Beckoning with your index finger is a gesture. Handwriting is not a gesture because the motion of the hand expresses nothing; it is only the resultant words that convey the information. The same words could have been typed – the hand motion would not be the same but the meaning conveyed would be.
> Sign languages are made up of gestures.
> Directing traffic is a gesture language.

A.3.b

C. Hummels, G. Smets and K. Overbeeke. 1998. "An Intuitive Two-Handed Gestural interface for Computer Supported Product Design." In I. Wachsmuth and M. Fröhlich (eds): *Gesture and Sign Language in Human-Computer Interaction*, 1998, p. 198.

> Most definitions of gesture boil down to the definition of Kurtenbach and Hulteen (1990) "A gesture is a motion of the body that contains information. Waving goodbye is a gesture. Pressing a key on a keyboard is not a gesture because..."
> ... Therefore, we employ the definition: "a gesture is a movement of one's body that conveys meaning to oneself or to a partner in communication." That partner can be a human or a computer. Meaning is information that contributes to a specific goal. For gestural product design, describing the surface of an object or using the object are considered to be gestures, because these contribute to the creation of the final product. However, getting one's hand to the place to start creation or manipulation is not considered a gesture, because it is a necessity to move your hand, but it does not contribute to the final product as such. The way you move your hand to reach this point is not important.

A.3.c

I. Wachsmuth. 1999. "Communicative Rhythm in Gesture and Speech." Invited talk, *Gesture Workshop GW'99*, 1999.

> **Gesture:** for the purpose of this paper it is sufficient to understand "gestures" as body movements which convey information that is in some way meaningful to a recipient.

17. These characteristics are: the excursion of a gesture (move away and return to a rest position), its peak structure, boundaries and symmetry.

4- Gesture and Sign-Language

A.4.a

F. Godenschweger and T. Strothotte. "Modeling and Generating Sign Language as Animated Line Drawings." Available at: http://isgwww.cs.uni-magdeburg.de/~godens/publications/asset.html

> A gesture in our application is composed of hand signs (both hands), the body movement and the facial expression.
> If a human is signing a gesture, a combination of dynamic and static gesturing is performed accompanied by facial expressions. The movements are carried out smoothly with varying velocity and controlled timing.

A.4.b

P.A. Harling and A.D.N. Edwards. 1997. "Hand Tension as a Gesture Segmentation Cue." In *Progress in Gestural Interaction*, pp. 75-88.

> Posture. A posture in this paper is considered to be a static hand shape where only the positions of the fingers are important. Hand orientation, location in space and any movement are not included.
> Gesture. A gesture is a series of postures over time that also includes information about hand orientation and location in space.

Appendix B
Concepts of Gesture in the Musical Domain

The definitions presented in the previous section relate to various fields. Could they be taken *as such* into the musical domain? If this is to be done, what would be missing in those definitions in order to characterize gesture in music?

In order to develop a deeper understanding of the meaning of gesture in the musical context, let us again analyze different researches on gestures, now in the musical domain.

1- Musical Gesture

B.1.a

E. Métois. 1996. "Musical Sound Information – Musical Gesture and Embedding Synthesis." PhD thesis, MIT, 1996.

> There is a diversified set of objects spanning the gap between the lowest-level musical intention (cognition, psychology, musicology) and a simple wave form (physics). These objects will be referred to as musical gestures and they should be seen as the features based on which musical intentions will eventually be recovered through some decision making.
> ... The gestures that are fed to the instrument are of a physical nature (fingering, pressure, energy, etc.) whereas the gestures resulting from our auditory perception are not. However, both present the ability to communicate musical intentions at a higher level than an audio wave form. The similarity of their level of abstraction motivated the author to label them both as Musical Gestures.

B.1.b

C. Drake. 1998. "Into the fundamentals of Musical Gesture." *Science et Vie Magazine*, hors série.

> "*Geste musical*" (musical gesture) is used as the equivalent of performer actions.

2- Gestural Coherence

B.2.a

M. Goldstein. 1998. "Gestural Coherence and Musical Interaction Design." *Proceedings of IEEE SMC98 Conference*, Oct. 1998.

> Music is a performing art, and part of the quality of the musical experience comes from the relationship between the player's physical technique and the sound that is produced. A listener can appreciate this connection visually (and viscerally) whether in a live concert or in the mind's eye while listening to a recorded performance. Our rich tradition of musical instruments has created a repertoire of gestures (bowing, blowing, banging, etc.) that are closely tied to familiar sounds.

3- Design of Virtual Instruments

B.3.a

A. G. E. Mulder. 1998. *Design of Virtual Three-dimensional Instruments for Sound Control*. PhD Thesis, Simon Fraser University.

> The word gesture has been used in place of posture and vice versa. The tendency however, is to see gesture as dynamic and posture as static. The notion of a musical gesture that at the time it occurs involves no actual human movement but merely refers to it is quite common. Obviously, musical expression is intimately connected with human movement, hence the existence of such an idiom. In the following, hand gesture and hand movement are both defined as the motions of fingers, hands and arms. Hand posture is defined as the position of the hand and fingers at one instant in time. However, hand posture and gesture describe situations where hands are used as a means to communicate to either machine or human. Empty-handed gestures and free-hand gestures are generally used to indicate use of the hands for communication purposes without physical manipulation of an object.

4- Gesture and musical composition

B.4.a

F. Nicolas. 1995. "Pour la beauté du geste." Conference presented at Université européenne de la recherche (Paris), June, 12.

> J'appelle geste un type particulier de moment musical, moment en général clairement identifiable dans mes œuvres car il comporte une forme et une découpe qui s'imposent tant à la lecture de la partition qu'à son écoute.[18]

18. I call gesture a particular kind of musical moment, which is generally clearly identifiable in my works because it contains a form and a cut-out that are obvious both on reading the score and on listening. [Translated by the authors]

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