# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temporal dynamics of connections. Representation from Kloeckl (2008)</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>The Schelleng diagram, in the force–position plane, for constant bow velocity</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Hacked moka with Max/MSP sonification patch</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>Cutting a carrot</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>The Gamelunch: a sonified interactive dining table</td>
<td>21</td>
</tr>
</tbody>
</table>
Designing Continuous Sonic Interaction

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Abstract

We claim that continuous interaction and multisensory feedback are key ingredients for successful interactive artefacts of the future. However, the complex web of sensors, actuators, and control logic that is necessary for exploiting such ingredients opens tremendous challenges to designers, who are used to visual thinking and discrete interactions. A method of research through pedagogical examples, called basic design and developed in some post-Bauhaus design schools, has been proposed as an effective mean to tackle the complexity of contemporary interaction design. A few such exercises, prototypical for different kinds of interaction primitives, are proposed here. Such exercises as useful as specifiers of design issues, and their solution can be sought through class assignment, shared observation, or self-reflection. Hearing is the privileged sensory channel for the proposed examples, and sonic feedback is realized through parametric control of sound synthesis algorithms.

Key words: Basic Interaction Design, Sound, Continuous Interaction

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1. Background

The focus of this paper is on design practices that exploit embodied, continuous interaction, with auditory display as the main channel for user feedback. The repertoire of audio sensors, actuators, processing and synthesis techniques that are widely accessible nowadays (Polotti and Rocchesso, 2008) make sonic interaction design the preferred framework for experimental design of continuous interaction in embodied interfaces. Interaction design insipier Norman (2007) illustrates the urgency of “naturalistic, continual feedback” by means of some auditory examples, such as the sound of the boiling water in the kettle (as an alarm) or the sound of a motor drill (as a continuous monitor). Here, we address situations where the user is continuously involved in object manipulation, and human-object interaction may be altered by specific design choices in continuous feedback. We are especially interested in the expressiveness and aesthetics that may emerge from elementary acts of use of everyday computational things. As observed by Hallnäs and Redström (2002b), “a proper aesthetics of computational things concerns time gestalt”, and there are “many similarities with musical expression”. Taking this observation very seriously, we believe that there is much to contribute to human-computer interaction by exploiting prior art and knowledge in sound and music analysis and synthesis.

In this framework, we exemplify extensions to classic pedagogical and research practices such as basic design and experimental phenomenology. Löwgren (2007a) proposed inspirational patterns as means of contributing to a design discourse. These also exploit traditional design practices and pedagogies by providing a set of abstract conceptualizations of interactions. Their main use seems to be in the area of analysis, critics, and nurturing of visions. Conversely, in this work we emphasize direct experimentation of alternatives in a constrained problem-based setting.

The paper is organized as follows: in the next two sections of this introduction, we provide the state-of-the-art of research on embodied interaction (Section 1.1) and an overview of the principles of basic design (Section 1.2). In Section 2, we illustrate three different and general interaction design themes tackled in the spirit of basic design:

• continuous coupling for the connection of two objects/devices (Section 2.1),
• cyclic actions with a regular time-periodicity (Section 2.2),
• the effect of a contradictory sonic feedback as a strategy for the refinement of sonic interaction design techniques (Section 2.3).
In the final part of Section 2, we briefly discuss further design cases and possible developments of the design problems that were presented. In Section 3, we draw our conclusions.

1.1. Embodied Interfaces, Continuous Interaction, and Sound

In Human-Computer Interaction, the virtues of direct manipulation (Shneiderman, 1983) have been widely appreciated and exploited. Its kernel principles can be summarized as: (i) Persistent representation of the object of interest; (ii) Physical actions or labelled buttons instead of complex syntax; (iii) Rapid incremental reversible operations whose impact on the object of interest is immediately visible.

In traditional WIMP/GUI interfaces, however, the principles of direct manipulation are applied to a world where the three key components of interaction (model, control, and view) are largely all in the digital domain, as there is physical separation between actions (mouse movements) and feedback (displayed output). An attempt to move control and view mostly into the physical realm led to Tangible User Interfaces (Ishii and Ullmer, 1997), which rely on really-direct manipulation of tokens having some representational capabilities. The fact that users are manipulating tokens eliminates a level of indirection, since part of the feedback is indeed where the action is. However, a hermeneutic level is often introduced, due to the nature of tokens as representations. This is what embodied interfaces (Dourish, 2001) tend to avoid by reducing mediations at a minimum, in the spirit of phenomenological thinking. In this work we focus on the physical, rather than the social, realities where interaction is embodied.

A disembodied interface, as most of existing machine interfaces are, tends to give a schizoid combination of perception and action. For the auditory world, this was well understood and extensively described by Murray Schafer (Schafer, 1994), who also coined the term *schizophonia* to indicate the separation from sound sources induced by recording and broadcasting means. The danger of schizophonia was felt much earlier by the composer Belá Bartók, who wrote in 1937 (Bartók, 1992) that “[...] the less foreign bodies are interposing themselves between the human body and the vibrating body or, the longest the time during which the human body controls the vibration is, the more the created musical sound will be immediate and, so to speak, human.” It is easy to generalize such observation to non-musical, everyday situations of interaction with artefacts.

Conversely, in embodied interfaces the tightness of the control–display loop gives a stronger sense of power which, albeit being subjectively desirable, may be abused. Schafer has been reported to say that it should not be allowed to have
sounds without knowing where they come from, so that you can destroy the source if you don’t like it. Indeed, destruction seems to be a compelling outcome of large-scale marketing of partially-embodied interfaces. For example, as soon as the Nintendo Wii console entered the market, a web site\footnote{http://wiihaveaproblem.com/} was launched to collect the experiences of people damaging the remote controller or hurting themselves because of excessive engagement in games.

Embodied interfaces tend to exploit continuous manipulations in a large extent. Before the industrial revolution, most of human actions in the world were essentially continuous. Opening a door meant grabbing the handle, turning it, and pushing it so that the door swings on its hinges. These continuous actions are far more prone to expressive manipulation than simple button triggering, as found for example in modern elevator doors. Indeed, as studies in musical acoustics show\cite{Juslin2002}, dynamic expressiveness can be induced through on-off switches only by temporal fluctuations of repeated triggering patterns. Being inherently expressive, continuous actions and gestures are supposed to be more “natural” than triggers. Naturalness here means that control is left to the human manipulator rather than transferred to some machinery. In Bartók’s words “less foreign bodies are interposing”. According to the tightness of sensory feedback to the handle, control can be more or less direct/physical. For example, sailing using the tiller is in a sense more engaging than using the wheel to control the rudder. In the latter there is a decoupling that allows application of smaller forces, but less feeling about the changes in direction of the boat.

When sustained feedback is elicited by triggers, the person acting on the trigger has the impression of autonomous life, and experiences a sense of causality. For example, in computer jargon, exceptions are \textit{thrown}, programs are \textit{launched}, etc. These are expressions similar to those used by the subjects of famous Michotte’s experiments to describe causality in motion patterns\cite{Michotte1963}. In interfaces, causality induced by automatization and triggers can be easily fooled by simultaneous extraneous feedback. In other words, one may easily get a fictitious sense of causality, as feedback comes just as confirmation for a complete gesture, and not as continuous monitoring of the gestural progress. Conversely, enactive and embodied interfaces are based on a closed loop based on motor skills, where control is exerted via continuous and simultaneous perception and action. Therefore, in such interfaces, experienced causality tends to correspond more closely to physical causality. This elicits aesthetic experiences that are now
recognized as crucial for the evaluation of an interactive artefact. Interfaces that have such a “tightly connected loop between [...] action and response”, enabled by continuous feedback, have been called pliable (Löwgren, 2007b).

1.2. Approaches in Design

When designing objects for multisensory continuous interaction, the controllable dimensions are many. There are countless possibilities for augmenting objects, but sensors and actuators should be considered together as they will certainly interfere in the action–perception loop. How can we tackle this complexity? One possibility is to think in terms of basic phenomena, constructively. So, we should look for fundamental interaction gestalts (Svanaes, 2000) that we exploit in “natural” interactions. Interaction gestalts naturally resonate with the concept of movement primitives, as they are considered in the literature of motor sciences as building blocks for complex motor skills (Schaal et al., 2003). Interaction gestalts may result from abstraction of actual interactions (Hallnäs and Redström, 2002a).

In a more holistic sense, some authors (Lim et al., 2007; Löwgren and Stoltzman, 2004) describe interaction gestalt as a the bridge connecting user experience and interactive artifact. Still, it is agreed that these gestalts are not properties of objects but are rather emerging properties of user-object interaction unfolding in time.

In post-Bauhaus design schools, prominent designers and educators such as Tomás Maldonado, Josef Albers, László Moholy-Nagy, and Bruno Munari, organized their classes around themes, by proposing exercises with well-defined objectives and constraints (Anceschi, 2006; Lupton and Phillips, 2008). Students acquired their basic compositional skills by searching for solutions to the problems, and by sharing and discussing the results. The elements to work with could be raw materials, ready-made artefacts, scientific facts, or algorithmic procedures. With this practice of basic design, research on the design fundamentals was advanced while teaching, in a very effective way if we consider the complexity of the themes. For example, in Albers’ color exercises (Albers, 2006 (1st. ed. 1963)), one may find a synthesis of centuries of scientific research on color perception, illustrated through a set of compelling examples. More recently, this practice has been extended to multisensory communication (Riccò, 2006).

In interactive contexts, managing the complexity of design is hard. Therefore, several contemporary theorists and educators (Anceschi, 2006; Findeli, 2001) claim that basic design, although in a renovated form that we may call basic interaction design, is still a valuable method. In particular, as a method of inquiry we proceed by analyzing actions, extracting interaction gestalts, and designing
exercises around a specific interaction gestalt (Franinović 2008). Exercises are typically tackled by constructively sharing observations, similarly to what experimental phenomenologists usually do to come up with explanations for phenomena that are complex and difficult to reduce to collections of separable and measurable mechanisms (Bozzi 1978).

To exemplify the basic interaction design method, we start from an analysis of actions in the kitchen (Visell et al. 2007) and consider the actions involved in preparing a coffee. We notice the interaction primitive of screwing the parts of the moka together, we abstract it as a case of dynamic connection, and develop an exercise around it (section 2.1). Then, in section 2.2 we focus on cyclic gestures typically performed in the kitchen, for example when cutting vegetables. We reflect on the nature of cyclic gestures, as different from discrete gestures, and on the continuous feedback that may accompany them. Finally, we propose two exploratory exercises aimed at developing an augmented sense of resistance when performing certain continuous actions, such as pouring and stirring. The four proposed exercises are indicative of a methodology that we are trying to follow in our work on continuous multisensory interaction.

In the exercises described in this article, we use objects (e.g., a moka pot) and materials (e.g., carrots) that have not been explicitly designed for our research or pedagogical purposes. Even though basic interactions are abstracted at the analysis stage, then their diverse realizations make purposeful use of found objects. The tradition of objet trouvé is deeply rooted in twentieth-century art. Besides being often more widely accessible and cheap than custom-made prototype objects and materials (Franinović 2008), using these readymades highlights the oscillatory balance between function and expression that should characterize design practices, especially in interactive contexts (Hallnäs and Redström 2002a). If, on one hand, this oscillatory attitude allows to understand the expressive features of objects in use, on the other hand it elicits new uses, or mis-uses, of objects. Again, in this respect music may provide many examples, ranging from the bow (from hunting tool to string exciter) to the turntable (from reproduction of music to generation, via scratching, of music) (Delle Monache et al. 2008).

2. Exercises in Sonic Interaction Design

In this section, we introduce and discuss three general design issues such as that of connections between objects, that of cyclically repeated actions, plus an investigation of the effect on the action of a contradicting and unexpected sound feedback. One specific design problem for each of the first two themes is pro-
posed and the implementation results are illustrated and discussed (see Sections 2.1 and 2.2). For the third theme, we ideated two different problems, one involving the manipulation of transformational aspects of the interaction and another considering the manipulation of structural properties of the objects involved in the interaction (see Section 2.3).

2.1. Theme I: Continuous coupling for connections in design

An important topic in product design is that of “connections”, i.e., how to create complex objects by joining simpler elements together. Different connections are characterized by different temporal dynamics. The act of joining and splitting parts unfolds in time, and the temporal exploration of the continuum between “attached” and “detached” can be represented pictorially via traces, as in figure 1.

The vertical axis could be interpreted as the degree of tightness in the connection. Although being a continuum, this tightness dimension can be categorically perceived as a small number of discrete states. For example, torque measurement systems\footnote{For example, see Ingersoll-Rand products} discretize the state of a screw connection into three stages: (i) torqued too low, (ii) OK, (iii) torque too high. For such systems, audio-visual signals have been designed to inform symbolically about the state, using a color visual code (yellow, green, red) and an auditory code based on counting (one, two, or three beeps).

2.1.1. The moka and the three stages of coupling

An example of critical connection is found in the moka coffee maker, a piece of Italian design of the nineteen-thirties, now in widespread use worldwide. In order to prepare a coffee one has to fill the boiling chamber with water, fill the

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Figure 1: Temporal dynamics of connections. Representation from Kloeckl (2008).
filter with ground coffee, and connect the three parts (boiling chamber, filter, and top container) by means of a screw connection. Tip sheets for moka pot brewing⁵ spend some words to describe how to screw the top and bottom together (“to get a tight fit is to hug the pot to your chest while you grab the two parts and twist them together. This does require a fair amount of arm and hand strength.”) and how to detect deviations from proper tightness (“if you can see steam escaping from the area where the top and bottom parts screw together”). The reason for such expressive descriptions is that the gesture of closing the moka is continuous, although it can be discretized into three stages: (i) loose, (ii) tight, (iii) too tight.

Evidently, it would be possible to apply some pressure or torque sensor to a moka and provide the same kind of discrete audio-visual feedback as it is given by torque measurement tools. However, this is likely to reduce much of the fascination and emotional engagement that people experience when exerting continuous manipulations of well-balanced mechanisms (Buxton 2005). So, the basic design exercise that we are facing here is

Problem 1.

Theme Continuous feedback for mechanical connections.

Objective Design the feedback for a screw connection, such as found in the moka, in such a way that the right degree of tightness in coupling can be easily reached.

Constraints The feedback should be continuous, non-symbolic, immediate to catch (or pre-attentional), and yet divisible into three clear stages.

Audio-visual symbolic signals, as the ones found in torque measurement systems, would result in a disembodied feedback, for two reasons: they enforce the discretization of gestures that are naturally continuous, and they rely on symbolic coding rather than on enactive experience. This is forbidden by the constraints. Notice that, in basic design exercises, constraints are usually supported by a rationale, although a different set of constraints may make perfect sense as a different exercise.

If choosing between visual and auditory feedback for the moka problem, audition is certainly to be privileged because, in temporal patterns and tasks, it affords

⁵See, e.g., http://www.sweetmarias.com/
higher resolution and it tends to prevail over possible non-coherent cues coming from other senses (Handel, 2006). After this observation, the design space is further constrained, and it reduces to sonic interactive feedbacks satisfying the requirements of problem 1. Still, the possibilities are countless, and one may exploit metaphors, analogies, or other design tricks to narrow the design space further. This is the point where we exploit prior art in sound and music computing. We approach problem 1 by inventing an analogy between two seemingly unrelated acts: screwing the pieces of a moka together and bowing a violin string.

2.1.2. The violin and the three qualities of playing

Bowed-string musical instruments, such as the violin, offer an interesting beacon to orient the approach to our sound design problem. Starting from the requirement of three discrete stages, violins indeed exhibit three main kinds of sonic quality, which can be explored by varying the three principal control variables: bow force onto the string, bow velocity, and bow position along the string. The oscillatory regime corresponding to “good tone” production is called “Helmholtz motion”. A graphical tool used to display at a glance the different oscillatory behaviors of a bowed string is the so-called Schelleng diagram (Serafin, 2004), schematically drawn in figure 2 for constant bow velocity. Two other regions are displayed on the sides of the region of good-tone (normal) production. Given a bow position and velocity, lower forces produce a “surface sound”, eliciting higher modes. Higher forces, on the other side, produce aperiodic “raucousness”.

Similarly, the region of “playability” can be highlighted on the force–velocity plane, for constant bow position. Different models of bow–string interaction can be analyzed in terms of the oscillatory regimes they produce, and Schelleng diagrams can be produced experimentally (Serafin, 2004). The wider the Helmholtz region results, the more easily playable the friction model is. A model that displayed a wide playability region, while at the same time being so versatile to reproduce a large variety of oscillatory regimes, is the elasto-plastic friction model (Avanzini et al., 2005).

By exploring the space of control parameters we can gradually step into different oscillatory regimes, and listeners are immediately capable to catch the quality of the physical actions associated with such sound manifestations. Namely, three distinct areas of effort (too low, ok, too high) can be readily associated with the three main tone-quality areas described by the Schelleng diagram. So, the requirements of our sound-design problem can be met.
2.1.3. Sonifying the moka

During a doctoral workshop at IUAV, we tackled problem by using preparatory materials (a disassembled moka, sensors and actuators, sound synthesis software modules) to put together convincing demonstrations that were experienced individually and discussed in group. This is the kind of research through pedagogy, or pedagogy through research, that basic design practices recommend. We applied a force sensor between filter and gasket of a moka, and used the force signal to control the elasto-plastic friction model, implemented as a Max/MSPE external within a supporting patch (see figure). Although one may map the sensed force directly to the force control parameter of the elasto-plastic model, clearer and more compelling transitions are obtained by covarying other parameters of friction, similarly to what the violinist actually does when performing a musical gesture. Moreover, as a general criterion in the sonification of everyday objects, it is preferable to make a sparse use of short sound pulses rather than modulate a sustained tone. Therefore, short friction bursts were generated by a pseudo-random process while the moka components were being coupled. The

[Figure 2: The Schelleng diagram, in the force–position plane, for constant bow velocity.]

[http://www.cycling74.com/products/maxmsp]
resulting sound dynamically changes its timbral quality as the coupling becomes progressively tighter. More precisely, the timbre moves gradually from a sound of glass harmonica for loose coupling, to assuming a rubber quality for the tight stage. When the coupling enters a “too tight” state, the sound resembles that of a squeaking hinge. Since in this work we focus on basic design methods rather than reproducible scientific experiments, we skip detailed report of the sound synthesis algorithm and parameters.

2.1.4. Discussion

The sonified moka was experienced directly by ten people who attended the workshop. The unanimous impression was that sound enhances the screw connection and makes the task more engaging. Feedback about the degree of closure was reported to be very natural. The experience of acting directly on the moka was judged to be very different from simply listening to the produced sound. The auditory feedback blends with the kinesthetic perception coming from exerting manual force on the moka components. Indeed, some people started to play with the moka and tried to push the boundaries of meaningful interaction, up to the point that, at the end of session, the force sensor was broken due to excessive pressure. This highlights a problem that is common to any object that affords
expressive interaction, at the point to elicit unexpected or excessive manipulation. When considering sound augmentation of everyday artefacts, the problem of localization of the loudspeaker is quite serious. The question is whether to attach a loudspeaker to the object or not. Physical constraints may impose a choice here. Otherwise, using an embedded loudspeaker usually enhances the unity of experience, even though the ventriloquist effect (Handel, 2006) guarantees a certain degree of coherence in perception even for loudspeakers displaced from the artefact. We tried both options during the workshop. When an actuator was directly attached to the moka everybody agreed that the sound became really part of the object, not only because of its apparent point of emission, but also for the acoustic properties of the aluminum chambers of the moka, which were affecting sound production.

A video documentation of the moka realization and of all of the following basic design exercises presented in the next sections is available on the web[7]

2.2. Theme II: Cyclic interaction. Multisensoriality and expressiveness in rhythmic tasks

Since the nineties some people started to look at continuous gestures in GUIs, like crossing targets or traversing hierarchical cascading menus, and tried to model them as limits of sequences of discrete gestures. The steering law was derived and applied in this framework (Accot and Zhai, 1997). However, when the task requires cyclic movements, experiments show that these movements cannot be simply treated as a concatenation of discrete gestures, as their rhythmic nature allows better exploitation of the physical properties of the neuromotor system. Actually, Fitts’ law has been reported to break down in rhythmic tasks, where performance turns out to be supported by much higher indexes of performance (Smits-Engelsman et al., 2002).

Some other people looked at what is in between starting position and final target in goal-directed movements, and discovered that there are kinematic patterns (Bootsma et al., 2004). Specifically, when difficulty is raised in a reciprocal aiming task, velocity profiles take an asymmetric bell shape, with an attack shorter than the release. So, there is much more behind point-like acts. The continuous support of discrete events contains much information that we are likely to exploit in everyday activities. In particular, the expressive content of our actions is largely mediated by these continuous gestures, even when they are aimed at

discrete events, like cutting a carrot evenly into pieces.

In music performance, preparatory and ancillary continuous movements are fundamental to convey the intended expressive character to a sequence of notes or drum strokes (Dahl, 2005). When attending the performance of a drummer we integrate visual and auditory information. While the former is supported by continuous profiles of an array of kinematic variables, the latter comes in discrete bursts of impact noise. The visual continuous stream and the auditory burst-based stream get integrated and synchronized according to different conditions. For example, the tempo of a rhythm and the naturalness of visually-perceived movements are known to influence the perceived synchrony (Arrighi et al., 2006). Also, the weight given to different sensorial channels may depend on the degree of expertise. Expert drummers tend to trust auditory feedback more than visual feedback when evaluating audio-visual synchrony of drum gestures (Pollick et al., 2007). These observations strongly support the use of auditory display for providing feedback in repetitive tasks. Indeed, as early as in 1991, Gaver et al. (1991) simulated a bottling plant and demonstrated that auditory display can support rhythmic activities even in collaborative environments. More recently, Lantz and Murray-Smith (2004) published an interesting study on rhythmic interaction with mobile devices. The two authors employ a robotic model denoted as Dynamic Movement Primitives (DMP) to recognize and classify a number of rhythmic gestures of people interacting with mobile devices, in order to provide and control a proper sonic feedback. The sonic feedback is intended to give continuous information about the quality of performance of a specific gesture based on the simple parameter of sound intensity: the more correct the gesture is, the louder the feedback sounds.

2.2.1. Rhythmic cutting in the kitchen

In the context of human-computer interaction, the action of rhythmic cutting has already been recognized as a source of useful information for achieving a sort of computer-assisted cooking (Kranz et al., 2007). A basic design exercise can be conceived to exploit the effectiveness of a well-defined feedback in such cyclic activities.

In several traditions of food preparation, cutting carrots in pieces of various shapes is considered a sort of performative activity, and sometimes even a key to meditation. This is certainly compatible with the observations of some anthropol-
ogists, who have observed how deeply the psychological states can be affected by shifts in tempo and intensity of cyclic gestures, such as in the case of drumming of shamans (Hodgkinson, 1996). These phenomena occur for enactive involvement in the action, and not by mere exposition.

Sensorized kitchen tools may enrich the enactive experience of food preparation, so that cutting precise rondelles becomes an act more easily achievable and enjoyable. For that purpose, we can play with the synchronization and balance between senses. The exercise may read as

**Problem 2.**

**Theme** Supportive and expressive feedback for cyclic continuous actions.

**Objective** Support coordination between the two hands in a cyclic task such as cutting carrots in rondelles, where longitudinal translation of the carrot is combined with the rhythmic action of cutting.

**Constraints** The feedback should be continuous and/or rhythmic, giving a sense of progress. It should emphasize jitter in the coordinated movements and the inherent expressiveness of gestures.

Problem 2 was tackled by the authors as a self-reflective basic design exercise. In other words, it built upon the shared experiences and discussions within the team of investigators. Self-reflection, or introspection, is the key tool of experimental phenomenology, or descriptive experimental psychology, dating back to the method of understanding by demonstration advocated by Franz Brentano in the 19th Century (Vicario, 1993). Basic design and experimental psychology are, in this respect, both using the practice of shared observation as the only possible way of assessing the properties of objects. The fact that this sharing may include students, naïve subjects, or just the investigators themselves, is of minor importance for the drawn conclusions, even though a wider panel may increase the robustness of results. Bozzi (1978) proposed the inter-observational method, where an experiment is performed by jointly exposing a small group of subjects to the stimuli. Since the members of the group have to agree on a report, problems of outliers and degree of expertise are largely reduced. At the same time, joint observation and discussion contribute to make the description of facts more stable and rich. In the design practice, it is clearly more convenient to let the team of designers wear the hat of subjects and provide an inter-observational report. Even though experimental phenomenologists recommend the direct participation of the
experimenter without a privileged position with respect to the subjects, we recognize a potential bias in reducing the group of subjects to the team of designers. However, a justification for this convenient choice may be obviously found in the difference in the objectives of experimental psychology and design.

The experimental setup (see figure 4) is made of three integrated sensing modules, namely a beat follower of the fracture sounds on the chopping board, a tracker of vertical knife acceleration, and a color tracker of the portion of the carrot being cut. A custom Max/MSP patch fuses the sensed data in order to provide a continuous (for the longitudinal progression) and rhythmic (for the cyclic action) sound feedback supporting the coordination between the two hands during action.

By means of a contact microphone applied to the chopping board, fracture sounds generated by cutting actions are detected. Changes in the spectral envelope of the incoming signal (attacks) are analyzed in order to supply adaptive beats as feedback for the user. The beat tracker is based on the mean of the elapsed time between successive cuts, computed over a few (4 to 6) exerted gestures.

Also, in order to estimate the size of the vegetable to be cut, we use a camera placed parallel to the chopping board and attached to one of its extremities. By color-tracking the orange of the carrot (green for zucchini), and by estimating the size of the orange blob, it is possible to detect the progress of the action, as displayed by the size of the integer part of the carrot. The mass value that decreases
from a certain maximum to zero is used to control the internal configuration of a friction sound model, providing a dynamic timbral transformation.

The knife is equipped with a 3 axis wireless accelerometer. It is part of the cutlery set of the Gamelunch (Delle Monache et al., 2007). A similar tool was proposed for context-aware kitchen environments (Kranz et al., 2007). During cutting, the vertical acceleration is sensed as a direct continuous manifestation of user gestures.

Each of the sensing modules has a specific role in the control of sonic feedback. Three kinds of rhythmic feedback were programmed as signal-processing manipulations of the sound captured by the contact microphone, and prepared for a comparative evaluation:

A beat with adaptive tempo, synchronous with the real stroke of the knife on the board;

B beat with fixed reference tempo at 75 BPM, with the user striving to keep it in upbeat with knife strokes;

C beat with adaptive and upbeat tempo.

These different feedback strategies are explained as follows.

**Beat with adaptive and synchronous tempo.** The tracked mean tempo drives a metronome in milliseconds, so that the user’s sonic interaction strives to be synchronous with the metronome-driven sound feedback. The user sets his tempo by cutting the first rondelles and, afterwards, interacts with the computer dynamically-generated beat. The feedback beat has an inertial time for changing its value in case of a persistent change in rhythm of the user action. On the other side, small and/or isolated deviations in periodicity of the cutting gesture do not influence the rate of the feedback beat, thus steering the user back to recover a regular pace.

**Beat with fixed reference tempo.** The reference tempo of the sound response is fixed at 75BPM (800 ms inter-beat interval). Furthermore, the sound feedback occurs on the upbeat with respect to the onbeat defined by the impact of the blade on the chopping board. Therefore, the temporal offset of such periodic feedback for a regime of regular cutting at 75BPM is 400 ms. Deviations from such reference target are subtracted from the offset, as if the metronome were spurring the player to get back in time. In other words, both in case of acceleration and deceleration, the delay time of the sound feedback gets shorter. From a psychological point of view, the user is impelled to respect the reference tempo by an upbeat
that, in case of deviations, occurs closer to her/his gesture generating a disturbing “gallop” time subdivision.

*Beat with adaptive and upbeat tempo.* The regular iteration of the gesture is driven by an upbeat sound response, which is delayed with respect to the impact of the knife on the cutting board, by an amount of time corresponding to the tracked mean tempo divided by two. Unlike mode B, here the sound feedback depends on the user pace, similarly to what happens in mode A. Mode C induces also some sorts of music-like interaction.

For all of the three cases, the impact of the knife on the cutting board is also sonically augmented. We considered a wide palette of physically-based impact sounds. In particular, we tested a number of cross combinations of different materials (glass, wood, metal, hybrids) and size in order to make a clear distinction between the impact sound and the feedback sound, the latter being the adaptive synchronous onbeat in mode A and the upbeat in mode B and C.

In addition, a continuous sound feedback informs about the nuances of the cyclic gesture, by mapping the sensed acceleration data of the knife on the pressure control parameter of a physically-based friction sound model. On one hand, this sound reinforces the rhythmic feedback. On the other hand, it provides an auditory indication of progress of the whole action. The latter sonic feedback is obtained by means of timbral variation of the friction sound: by raising the pitch and by making the sound sharper, a sense of reduction of the mass of the vegetable is conveyed. More in detail, the sound corresponding to the entire carrot or zucchini is low-pitched and spectrally richer, and it becomes slimmer and higher when the carrot or zucchini mass diminishes.

2.2.2. *Discussion*

We tested the three proposed solutions with two different kinds of vegetables: carrots and zucchini. It was evident that the difference in hardness between the two vegetables induces different gestures for accurate rhythmic cutting. In the case of zucchini, the user may prefer to lift the whole knife, so that cutting occurs mainly because of the weight of knife and forearm. In the case of carrots, cutting is more effective if the tip of the knife is kept on the board, thus providing a pivot for the up-down movement of the knife itself. A number of experiences were freely performed and audio-visually recorded. According to the reported feeling of the users/designers, and to an analysis of the video recordings, we were able to qualitatively evaluate the three different modes.
**Beat with adaptive and synchronous tempo.** In mode A the whole gestural cycle appears to be fragmented in two stages, corresponding to dropping and lifting the blade. The performance seems to chase the sound feedback, with fast accelerations in the final part of each of the two cycles, as if each sound feedback acted as a new start. Abrupt reactions and a small overall gesture width can be noticed. As an effect, the blade leans on the board for a shorter time, as compared to the other two modes. Maintaining a perfect synchronism in mode A seemed to be more unnatural and, thus, less successful when compared to modes B and C.

**Beat with fixed reference tempo.** Mode B seems to require the attitude and skills of a player performing music with a metronome. The nuance of the gesture is quite regular during cutting and holding, while it accelerates subtly in the final part of the lift. The descent is quick, as if waiting for the sound feedback and then chasing the next cut, albeit not as nervous as in mode A. In fact, the overall width of the gesture is larger than mode A even if smaller than mode C.

**Beat with adaptive and upbeat tempo.** Mode C seems to be the most effective: it affords maintaining a regular pace while not being strictly tight to a fixed reference tempo as mode B. The fact that in mode C the sound feedback comes after each stroke, and before the next one, appears to be a better listening reference point, since it can be pre-attentively related to the sonified impacts of the knife on the board. Somehow, mode C recalls the “tick-tack” of a clock and this is possibly the reason of its effectiveness: a binary subdivision of time that can be very easily interiorized by the user. From the video analysis of the cutting action, it appears evident how in mode C the gesture is wider and more fluent than in the other two modes. Furthermore, the sound feedback tempo adapts to any persistent change of rhythm in the cutting action, making the action more flexible and allowing the cutter to act in a more relaxed way with respect to mode B. For example, a slower beat at the beginning of the action as well as at the end, when the blade gets nearer to the fingers, is often opportune.

The continuous feedback due to the knife movement spurred contradictory observations. While it was judged as a useful and consistent reinforcement of the rhythmic feedback, it was also described as potentially annoying. Nevertheless, the timbre change providing information about the action progress received an unanimous positive evaluation. The “shrinking” sound feedback induces people to withdraw the fingers from the last bit of carrot well in time not to have a finger cut!
2.3. Theme III: Use of contradictory feedback in interactions

The third theme that we are proposing has been extensively explored for the realization of an interactive installation based on everyday objects and actions, called the Gamelunch (Delle Monache et al., 2007; Polotti et al., 2008; Delle Monache et al., 2008). The objects are an ordinary table, some cutlery, and other dining items (see Figure 5). The actions are those used by people when preparing and consuming food and drinks: pouring, cutting, mixing, etc.. While developing the Gamelunch we extensively used a basic design approach, especially when designing the auditory feedback for prominent actions. Each of these design tasks was defined as a problem with objective and constraints. The dominant objective was that of providing a sensory contradiction to the actions that were being performed.

When continuous feedback is coupled to continuous movements, the coordination of different sensory channels is known to affect the action (Lagarde and Kelso, 2006). For example, audition may convey a better sense of velocity or acceleration as compared to vision or haptics, thus eliciting smoother trajectories in a target-reaching task (Rath and Rocchesso, 2005). Little research has been done to investigate the emotional impact of continuous sounds on continuous gestures, even though it is recognized, in the area of product sound quality, that evaluating the feel of an object in use is different from rating different sounds presented over the headphones (Spence and Zampini, 2006). In the area of emotional design, it has been observed that users interpret displays as emotionally expressive even if there is no explicit representation of emotion (Boehner et al., 2005). So, it becomes possible to “distort” a display to manipulate its emotional impact.

Playing with the relationship between different sensory channels gives the opportunity to exploit the power of contradiction in multisensory interaction. A possible strategy is in fact to distort one (or some aspects of one) of the displays, while preserving the natural characteristics of the other ones. Empirically, we observed that by properly designing a sonic feedback, one can strengthen or resist an action. Producing a sonic feedback, that is unexpected with respect to one or more aspects of a specific interactive context, has interesting effects on the performed actions. By means of what we could consider a manipulation of both cognitive expectations and emotional impact of the feedback, one is able to stress the relevance of a specific portion of the information conveyed by the distorted channel. Experimental realizations of counter-actions have been tested as part of the Gamelunch installation. For the purpose of having a stable and portable configuration, a common table has been hacked by embedding a number of sensors, the acquisition boards, loudspeakers and cables in the tabletop. Magnetic, light,
Figure 5: The Gamelunch: a sonified interactive dining table.
and force sensors are invisible to the user and their purpose is to make the objects laying on the table sensitive. These objects are a couple of bowls and two dishes. Then there are objects that can be handled: a knife, a fork, a couple of bottles, a tray, and a decanter, all made sensitive by means of 3-D wireless accelerometers. Embedding the loudspeakers in the table proved to be a valuable choice, since the improved localization of the sound sources enhances the embodied qualities of the objects. All of the following themes and problems of this paper were developed within the Gamelunch environment.

In the Gamelunch, as a general principle, the manipulation of sonic feedback does not affect the consistency with gesture, in the sense that when the action is more intense, the sound feedback is energetically consistent in terms of loudness and/or increased number of events. In other words, the feeling of causal continuous control of the action is maintained. This has been experienced as fundamental in order to preserve the veridicality of sonic feedback and avoiding the risk of arbitrariness that otherwise would occur. Under constraints of energetic consistency, two main kinds of contradiction have been explored, one related with the temporal development of actions, and the other deeply connected with the nature of materials that are being manipulated. These two modalities correspond to what Warren and Verbrugge (1984) called transformational and structural invariants, respectively.

2.3.1. Manipulating transformational invariants

The design of transformational manifestations of actions was addressed for the case of pouring a liquid from a decanter. In terms of basic design, the problem of the resisting decanter can be formulated as:

**Problem 3.**

**Theme** Contradictory feedback for continuous actions.

**Objective** Design the feedback for a pouring action, so that a perceived resisting force contradicts the easiness of liquid streaming.

**Constraints** The feedback should be continuous, non-symbolic, immediate to catch (or pre-attentional), and consistent with the underlying physical process (e.g., more flow more loudness).

In the Gamelunch, we use a solid-friction sound model (Avanzini et al., 2005) to sonify the inclination of the decanter, giving the feeling of a resisting force.
that contradicts the (opposite) effect of liquid flowing and of the decanter getting lighter. The same principle is also exploited for sonifying manipulations of a fork. In this case, a squeaking sound is generated when the fork is lifted. A feeling of heaviness in the action, and particularly of resistance in the elbow was unanimously perceived by the numerous users who experienced the Gamelunch. Furthermore, two opposite kinds of reactions were registered among occasional users of the decanter and the fork: some of them interrupted their action (as if they were recalling they are on diet), some others were stimulated to emphasize the gestures, thus exploiting the performative potentialities of these objects.

2.3.2. Manipulating structural invariants

The second direction of distortion consisted in contradicting something not directly related to the action as, for example, the material of the objects involved in the interaction. One case study was that of the action of stirring a soup:

Problem 4.

Theme Contradictory feedback for continuous actions.

Objective Design the feedback for a stirring action, so that a perceived resisting force contradicts the easiness of stirring a liquid as well as the liquid identity.

Constraints The feedback should be continuous, non-symbolic, immediate to catch (or pre-attentional), and consistent with the underlying physical process (e.g., more movement more loudness).

We converged toward a realization where the sonic feedback is similar to the sound of a tool mixing a sandy material, in contradiction with the visual (and olfactory) image of a soup in the dish. An effect of resistance to movement due to the acoustic manifestation of solid obstacles in the soup is evidently perceived.

Contradictory feedback may be exploited in contexts where some actions have potentially serious consequences. It is well known that warning messages tend to be ignored in routine situations (Raskin, 2000). It may well be the case that some additional resistance introduced via multisensory emotional stimulation in presence of critical gestures induces higher attention as in the case of the decanter and the fork. This is particularly important in future objects, such as cars, with a high degree of autonomy (Norman, 2007). For example, the sustained experience of effort proved to be an effective design ingredient to prevent modal errors in interfaces (Raskin, 2000).
2.3.3. *Facilitatory contradiction in sonic feedback*

Our exercises with contradictory feedback can be also exploited by subverting their objectives. Instead of aiming at contrasting an action one could pursue the opposite effect of facilitating it by means of the same sound design strategies based on contradiction. For example, when the sound of a knife is that of a fast and smoothly sliding blade, the action of cutting will be perceived as easier and smoother. In terms of basic design, the problem of the “swift” knife could be formulated in the same way as Problem 3. It is sufficient to invert the requirements of the objective, i.e. dropping the restraining/limiting task and asking, instead, for a facilitating effect.

As a generalization, the goal is to be able to design a sonic feedback for any given action, so to mislead the perceived effort, in particular providing the feeling that the action is more comfortable and straightforward than it actually is. As in the previous cases, the feedback should be continuous, non-symbolic, pre-attentional, and consistent with the underlying physical process.

The case of the knife is focused on the action, i.e. on the manipulation of transformational invariants, similarly to Problem 3. A “swift” counterpart of the solid soup of Problem 4 can also be obtained by playing with the material identity, i.e. with structural invariants. For example, a liquid sound feedback in the action of dressing a salad can fool the perception of material in the bowl and make people feeling the action lighter than it is. In the Gamelunch implementation of this specific case, we noticed how a distortion of the action can occur as well in the sense that people are induced to steer the salad by means of a circular movement as if it were liquid.

Generally speaking, the idea is to define strategies for designing contradictory sonic feedbacks, so to mislead the perceived consistency of what one is manipulating, in particular providing the feeling that the manipulated material is softer than it actually is, thus facilitating the action. In this case as well, the feedback should be continuous, non-symbolic, pre-attentional, and consistent with the underlying physical process.

In the Gamelunch setup, we obtained a similar effect with a fork, by changing arbitrarily the sound produced by the action of piercing a bit of food. A gummy sound could give the sensation of an easy and pleasant action even if one is dealing with a hard bit of solid caramel stuffed with nuts.

Even if rigorous experimentation has not been conducted yet, it is remarkable how most of the people who experienced the Gamelunch agreed on the effectiveness of the distortion in terms of acquiring consciousness of the role of the sonic feedback.
feedback. The principle of contradiction seems to be an extremely effective way to bring the attention of people on the sound feedback of their actions and to make them conscious of the importance of the information they receive through their auditory channel, often underexploited or even neglected.

2.4. Other interaction primitives

In the early sixties, at the Ulm design school, Tomás Maldonado ideated the Antiprimadonna (Anceschi 2006), an exercise with the objective of training designers to produce non-hierarchical visual patterns. The idea was that, after extensive practice with this task, the designer would be better in letting hierarchies emerge in a controlled way.

Similarly the exercises on contradictory feedback can be considered as a training towards a more aware design of structural and transformational invariants of sonic feedback for interactive systems in a “straightforward” way.

In case of structural invariants, the goal could be to exploit the sonic identity of materials for supporting continuous actions by providing the feeling of the effect of the action on the state of the involved materials/objects. An example could be the case of liquids or powders that produce strong physical or chemical effects in little quantities: the sound should help to perform an action involving these materials attentively. This can be achieved by sonically representing the properties of the substances. In the Gamelunch, we implemented two bottles, one for the oil and the other for the vinegar, and designed two corresponding sounds. The quantity of the poured liquid and, thus, the effect of the substance on the food are represented by the sound activated when the bottle is shaken. Provided that the loudness parameter is a hint about the quantity and considering the case of the vinegar, the question is: how soar will the salad be after pouring that acidly-sounding-liquid? Given a good sound design, this could be easily “tasted” by our ears.

Transformational properties can be exploited as well for controlling interaction. A possible approach consist in anticipating the time of occurrence of the sonic feedback, in order to provide sonic cues about the consequences of an action that is in its initial phase. For example, we sonified a tray with some glasses on top of it: as far as the tray is slightly inclined a dripping sound works as an alert, anticipating what would happen, if the tray would be further tilted.
3. Conclusion

We conclude with a simple remark. The examples and problems here proposed and discussed can be considered as exercises in basic interaction design. Clearly, the kitchen scenarios are only instrumental to experimenting with continuous multisensory interaction under well-defined constraints. There are many other environments and tools that may benefit from carefully-designed multisensory feedback, in terms of accuracy, safety, affection and engagement. In this sense, we see this work as a reference for a more general line of investigation in sonic interaction design.

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