Supporting expert creative practice

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To my mother.

ABSTRACT

This thesis focuses on the design of interactive tools that support expert creative practice in graphic design and contemporary choreography. Graphic design has a much stronger digital tool dependence than choreography, and designers have at their disposal a variety of sophisticated software tools to choose from. However, it has been shown that current commercial systems do not support their practices flexibly, and designers often have to manage the progression of their creative ideas and principles in manual ways, or resort to programming. Choreography, on the other hand, is distinctively an artistic practice, thus typically deals with under-constrained problems. Contemporary choreographers rarely have access to tools specifically designed for choreography. In addition, they have their own representations of choreographic ideas and are often reluctant to adopt another practitioner's methods, which makes the design of suitable interactive tools a challenging task.

In spite of their differences, designers and choreographers have a common need: To lay out elements in space, or space and time. Designers manipulate graphical elements mostly in space, and choreographers organise movement in space and time, with the collaboration of dancers. They have to consider characteristics of movement, such as intention and dynamics, and the dancers' roles in this context. Designers and choreographers are both guided by personal underlying principles, which they often challenge or discover during their creative practice. These principles, together with the environment in which their projects develop, establish relationships between the elements and ideas with which they work, constraining their creative process. I argue that to build powerful, grounded software tools to support expert creative practice we need to let users interactively define and manipulate *constraints* and not just *content*.

In Part I, I focus on spatial constraints in graphic design, and in particular, in alignment and distribution. I first study how current users of graphical editors struggle with alignment and distribution when creating a layout (Chapter 4). I identify the mismatch between their perception of these concepts and how current systems handle them. Based on the findings, I introduce *StickyLines* (Chapter 5). *StickyLines* is an interactive tool that provides explicit representations of alignment and distribution constraints and better matches how users perceive relationships between graphical objects. Through user studies, I show that *StickyLines* is faster

and requires fewer user actions than traditional command-based strategies for complex layouts, and that designers quickly adopt it and appropriate it for their own needs.

In Part II, I address spatial and temporal constraints in contemporary choreography. I study how choreographers capture and manage their ideas during the creative process, with a focus on the artefacts that they generate (Chapter 6). I synthesise their commonalities into the *Choreographic Object-Operation* theoretical framework, which feeds a set of implications for design. Building on the results, I introduce the design of *Knotation* (Chapter 7). *Knotation* is a pen-based mobile tool that allows choreographers to sketch choreographic ideas and make them interactive. Through user studies and design iterations, I show that *Knotation* supports choreographers' diverse approaches, allowing them to focus on representing constraints, movement, or a combination, and to rely on the tool for exploration, documentation, or both. I then study in-the-wild collaboration in choreography when mediated by *Knotation*, through two longitudinal field studies (Chapter 8). From the results, I derive implications for the design of tools to support collaboration in dance when exploring and documenting ideas.

Based on the findings from both parts, I reflect on the challenges of designing interactive tools to support the creative practice of designers and contemporary choreographers (Chapter 9). I highlight that although their creative product is fundamentally different in nature, these professionals' creative process can be approached with a common strategy: The reification of structures through interactive *substrates* that articulate *content* and *constraints*. Finally, I conclude with limitations and perspectives for future research (Chapter 10).

RÉSUMÉ

Cette thèse porte sur le design d'outils interactifs pour aider la pratique créative d'experts dans les domaines du design graphique et de la chorégraphie de danse contemporaine. Contrairement à la chorégraphie, le design graphique est fortement dépendant des outils numériques, et les designers disposent d'une grande variété de logiciels sophistiqués. Cependant, les systèmes disponibles sur le marché ne sont pas assez flexibles pour accompagner les designers dans leurs pratiques. Il n'est pas rare que les designers aient besoin de modifier leurs idées à la main ou de les programmer eux-mêmes pour les mener à bien. Par ailleurs, la chorégraphie, en tant que pratique artistique, fait face à des tâches moins contraintes. Les chorégraphes ont rarement accès à des outils qui leur sont dédiés. La représentation des idées étant propre à chacun, ils sont souvent réticents à adopter les méthodes d'un.e autre artiste. Cela rend difficile la conception d'outils adaptés à leurs besoins. Malgré leurs différences, les designers et les chorégraphes ont un besoin commun: disposer des éléments dans l'espace, ou dans l'espace et le temps. Les designers manipulent les éléments graphiques principalement dans l'espace, et les chorégraphes en collaboration avec des danseurs organisent le mouvement dans l'espace et le temps. Ces derniers doivent tenir compte des caractéristiques du mouvement et des rôles des danseurs. Les designers et les chorégraphes sont guidés par des principes personnels qu'ils découvrent ou remettent en question au cours de leur pratique créative. Ces principes, ainsi que l'environnement dans lequel leurs projets sont développés, contraignent leur processus créatif. Je soutiens que, pour construire des logiciels puissants et ancrés dans les pratiques des utilisateurs permettant d'étayer la pratique créative d'experts, nous devons laisser les utilisateurs définir et manipuler les contraintes (et pas seulement le contenu) de manière interactive.

Dans la Partie I, je me concentre sur les contraintes spatiales dans le design graphique. J'étudie comment les utilisateurs des logiciels graphiques ont des difficultés avec l'alignement et la distribution lors de la création d'une mise en page (Chapter 4). J'identifie alors le décalage entre leur perception de ces concepts et la façon dont les systèmes actuels les gèrent. Sur la base de ces observations, je présente *StickyLines*, un outil interactif qui offre une représentation explicite de l'alignement et la distribution (Chapter 5). Au travers d'études utilisateurs, je montre que *StickyLines* est plus efficace que les stratégies basées sur les commandes,

et que les designers peuvent le prendre à main rapidement et se l'approprier.

Dans la Partie II, j'aborde les contraintes spatiales et temporelles dans la chorégraphie de danse contemporaine. J'étudie comment les chorégraphes capturent et manipulent leurs idées, en mettant l'accent sur les artefacts qu'ils produisent (Chapter 6). Je synthétise leurs points communs dans le cadre de *Choreographic Object-Operation*, qui fournit un corpus d'implications pour la conception. Sur la base de ces résultats, je présente *Knotation*, un outil mobile permettant aux chorégraphes d'esquisser des idées et de les rendre interactives (Chapter 7). Au travers d'études utilisateurs, je montre que *Knotation* soutient les diverses approches des chorégraphes, leur permettant de représenter des mouvements, des contraintes, ou une combinaison des deux. J'étudie également la collaboration dans des situations réelles via deux études longitudinales sur le terrain en utilisant *Knotation*, et je tire des résultats des implications pour la conception (Chapter 8).

Sur la base des réponses apportées par ces deux parties, je réfléchis aux défis de conception des outils interactifs pour les designers et les chorégraphes contemporains (Chapter 9). Enfin, je conclus par les limites de ces travaux et les perspectives de recherche future (Chapter 10).

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I am immensely grateful to the *ExSitu* team and proud of the students that I shared these years with. It was a pleasure to be part of a group where people are so aware of others' projects (and struggles), genuinely helping each other. I am particularly thankful to Carla Griggio, Germán Leiva, Nolwenn Maudet, Nacho Avellino, Stacy Hsueh, and Philip Tchernavskij. Nolwenn deserves a special mention: Our collaboration was fun, smooth and incredibly productive. From her I learnt a lot about design, and more importantly, how to keep a healthy work-life balance.

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CONTENTS

1 INTRODUCTION

In this dissertation, I explore how to design interactive tools that support expert creative practice, with a focus on graphic design and contemporary choreography. To develop their creative ideas, designers and choreographers need to lay out elements in space, or space and time. Designers work with graphical elements that they manipulate primarily in space, and choreographers work with dancers, organising movement in space and time. Both types of creative professionals do so according to their own set of underlying principles, which they might even generate, discover, or challenge during the creative process. I seek to enhance the interaction between these users and their personal representations of creative ideas, providing a mix of user-defined constraints and flexibility, through interactive tools grounded in users' practices.

Creativity is an inherently complex human phenomenon that has been studied extensively in psychology and creativity research, and more recently in human-computer interaction (HCI) (Frich et al., 2018a). According to Ben Shneiderman (2000), *"technology has always been part of the creative process, whether in Leonardo's paint and canvas or Pasteur's microscopes and beakers"*. Understanding creative processes when mediated by technology, be it analogue or digital, is still an open question in HCI, as well as how to design for supporting these processes across different levels of expertise and disciplines. Moreover, Shneiderman (2009) called the development of creativity-support tools (CST) a *"grand challenge for HCI researchers"*.

Creativity exists not only in eminent works of art and scientific breakthroughs, but also in everyday life and in the process of learning new skills. At a personal level, creativity can even be seen as *"a sign of mental health and emotional well-being"* (Simonton, 2000). Kaufman and Beghetto (2009) proposed a distinction between four types of creativity: *mini-c* (creativity in a learning process), *little-c* (everyday creativity), *Pro-c* (professional-level creativity), and *Big-C* (eminent creativity). I am interested in the design of interactive tools for *Pro-c* creativity, supporting the expert creative practice of professionals.

In this thesis, I focus on designers and contemporary choreographers, as they push the limits of technology and reveal innovative ways of expressing and exploring ideas (Maudet et al., 2017; Birringer, 2002). They appropriate the available technologies, from sophisticated commercial systems to physical paper notebooks, to meet their creative needs (Jalal, 2016; deLahunta et al., 2004). As design is a broad discipline, I specifically target designers who work with visual layouts, such as graphic and interaction designers.

Differences across a variety of dimensions make design and choreography interesting cases to study and compare. In the first place, the design fields I consider are marked by a much stronger digital-tool dependence than contemporary choreography. On the other hand, choreography is distinctly an artistic field and thus under-constrained, while the border between design and art is a blurry one. Designers can work individually, while choreographers typically need at least one dancer with whom to interact, unless they are composing a solo to perform themselves.

I argue that designers and contemporary choreographers both need to define not only the content in their projects, but also the *constraints* that govern this content. Although HCI researchers are becoming increasingly interested in creativity constraints, Biskjaer and Dalsgaard note that *"no comprehensive, cross-disciplinary theory of creativity constraints has yet been introduced"* (Biskjaer and Dalsgaard, 2012). For this reason, I subscribe to a specific definition that describes creative constraints as *"explicit or tacit factors governing what the creative agent/s must, should, can, and cannot do; and what the creative output must, should, can, and cannot be"* (Onarheim and Biskjaer, 2013). This definition involves all the factors *"that might affect creative agency, spanning from technical and practical to social and cognitive constraints"* (Onarheim and Biskjaer, 2017). I draw from Jon Elster's (2000) distinction between *intrinsic* constraints (given by the materials), *imposed* (by stakeholders; e.g. deadlines and budget), and *self-imposed* (by the agent, expecting a more creative result).

During their creative process, designers and contemporary choreographers often need to organise elements in space, or in space and time. Designers work with graphical objects that they manipulate primarily in space, e. g., shapes, images, text, as well as their graphical properties, such as a colour, position, size. Contemporary choreographers work with dancers, shaping movement in both space and time, and have to deal with characteristics of movement, such as intention and dynamics.

Designers need precise, yet flexible software tools to define the constraints underlying the structures and rationales in their creations (Maudet, 2017). In particular, they often need to establish spatial constraints between the graphical objects in a layout, for example, aligning and distributing them in two-dimensional space. In this thesis, I chose alignment and distribution as concrete examples of spatial constraints because they represent a cumbersome, recurrent problem, yet small enough to be studied in depth.

Contemporary choreographers, on the other hand, work with spatial constraints but also with temporal and more complex constraints, e. g., movement qualities, metaphors, intentions. Since graphical elements are organised following the designers' rules, designers generally have more control over their final product. Contemporary choreographers' compositions, instead, are typically performed by people, so choreographers need to consider the interplay between dancers and constraints: Because dancers have agency, they can interpret and redefine them.

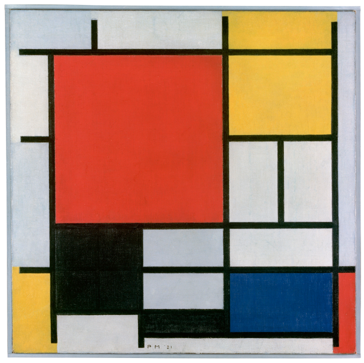

Figure 1: Piet Mondrian's *Composition en rouge, jaune, bleu et noir* (1921). Mondrian limited his vocabulary to primary colours (red, blue, yellow), primary values (white, black, grey), and primary directions (horizontal and vertical). Source: Wikimedia Commons.

I want to support designers and contemporary choreographers in defining and manipulating constraints, with an emphasis in the self-imposed. These can be, for example, sources of inspiration that the professional chooses to guide the creative process, such as a symbol, a number, a piece of poetry, or specific combinations of visual properties. A deceptively simple example is Mondrian's composition based on colour and shape constraints (Fig. 1).

Designers often represent their creative ideas — including content and constraints — using personal, ad-hoc approaches. They frequently have to handle these representations and their evolution in manual ways, as current digital tools do not support their practices flexibly (Maudet, 2017). Unlike designers, contemporary choreographers rarely have access to digital tools designed for choreography. Moreover, we lack a deep understanding of how contemporary choreographers manage their ideas and the digital and analogue tools they use. In addition, each choreographer develops their own set of methods and styles, and they sometimes explicitly challenge the field's rules and their own ideas and ways of working, drastically modifying their approach from one project to the next (Blom and Chaplin, 1982; Groves et al., 2007; Morgenroth, 2004; Weiss, 2018).

My goal is to allow these professionals to define and shape their ideas from the beginning of their creative process, when they might not know yet how they will solve the problem they set for themselves. I want to support them in expressing and exploring their creative ideas by letting *meaning* emerge in the process. I envision an environment where users can express constraints, so that they can discover patterns, try alternatives and change their minds flexibly, generating and refining their own creative principles along the way.

I believe that this requires grounding tools deeply in users' practices, but *appropriable* at the same time (Mackay, 1990). I intend to design tools that users can adapt to their own needs over time, since this encourages innovation while increasing the expressive power of tools. As Kristina Höök (2004), I advocate for involving the user as an *"active co-constructor of system functionality"*, while I also deem fundamental to take a responsible role as a designer, one that is accountable for the design decisions.

My approach on supporting the creativity of these professionals does not try to make them creative, as they already are extremely creative. My work is not oriented to increase their efficiency in terms of time or error either: In creative endeavours, quality is typically more valued than quantity, errors can be seen as challenges, and a longer time spent with a creativity-support tool could indicate that the user is engaged with it and with the task (Carroll et al., 2009). Instead, I want to leverage users' skills so they can be in control of their creations and explore rich, personal ways of expressing ideas.

1.1 THESIS STATEMENT

I argue that by letting users interactively define and manipulate *constraints* together with the content that they want to create, we can build powerful software tools to support expert creative practice. Tools should not enforce a particular set of constraints, but to the extent possible, allow users to embed their own. Users should be able to represent these constraints and adjust them in exploratory ways to shape their ideas, from the beginning of the creative process throughout the transition to more refined stages. Tools should be grounded in users' practices, yet let *meaning* emerge along the way, giving control to the user without prescribing a rigid approach. Moreover, tools should support not only the representation of users' existing creative principles but also the discovery and generation of new ones. *StickyLines* and *Knotation*, the interactive systems that I propose, take a step in that direction and show how can we design grounded, appropriable tools in this context, opening a path for researchers and designers to delve deeper.

1.2 RESEARCH APPROACH

Designers and contemporary choreographers have their own individual styles and methods that evolve over time and across projects, which makes it difficult — or even impossible — to represent their practices using only theoretical models. The nature of their creative fields requires the combination of rigorous observations of real users, and solid theoretical bases, in order to design and evaluate digital tools that suit users' needs. For these reasons, my thesis involves a variety of user-centred methods that triangulate between *observation*, *design*, and *theory*, as in Mackay and Fayard's (1997) framework for HCI research (Fig. 2). I draw from

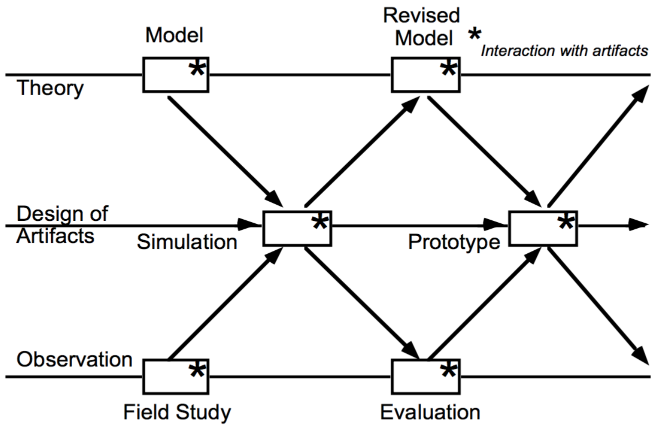

Figure 2: Mackay and Fayard's framework: HCI research triangulates around theory, design of artefacts, and observation. Source: Mackay and Fayard (1997).

empirical studies of designers and contemporary choreographers carried out during this thesis, and theories in HCI (described in Chapter 2), to design artefacts for supporting expert creative practice. I built and evaluated design artefacts (*StickyLines* and *Knotation*) using several methodologies, including technology probes, structured observations, field studies and laboratory experiments. These artefacts, as Mackay and Fayard's argue, *"constantly evolve and influence or change models at the theoretical level and observations at the empirical level"*.

1.2.1 *Critical object and critical incident interviews*

Designing for creative professionals with a user-centred approach requires a better understanding of their actual work practices. Interviewing practitioners about recent, specific projects allows researchers to capture stories that serve both to uncover particularities of the their creative processes, and to inspire new design ideas.

The *critical incident technique* (Flanagan, 1954) grew out from studies in the U.S. Aviation Psychology Program after World War II, and was initially used to discover what led to aeroplane accidents. It sought to collect *"direct observations of human behavior in such a way as to facilitate their potential usefulness in solving practical problems"*. The technique relied on the report of *critical* incidents: examples of *"extreme behavior"* with a *"special significance"* for the observers of an activity. According to Flanagan, *"reporting of facts regarding behavior is preferable to the collection of interpretations, ratings, and opinions based on general impressions"*. In addition to being critical, incidents had to be recent, as they were reported from memory. Interestingly, Flanagan noted that *"critical* *incidents represent only raw data and do not automatically provide solutions to problems*", requiring an appropriate analysis after their collection, as well as procedures to improve the observed activity.

I used a variation of the technique to conduct *critical object* interviews (Mackay, 2002) with users of graphical editing tools, designers, dancers, and contemporary choreographers along several studies. I invited them to show me the artefacts they generated in recent projects and guide me through their creation step by step. I probed for specific stories sparked by these artefacts, to count with a grounded, detailed reconstruction of the process. These stories help researchers understand what participants actually did, rather than getting a description of how the process should ideally work, and provide rich, comparable data about participants' challenges and decisions. I focused on breakdowns (specific problems faced by participants, involving a piece of technology or not), and in user innovation and appropriation (their personal strategies or workarounds, especially when dealing with breakdowns). I probed also for surprises, and bright spots (memorable situations in which they had a rewarding interaction with a tool, analogue or digital, or with a person during the creative process). These different types of stories are fundamental in the design of solutions that tackle users' problems, but that also leverage current successful practices.

I also used the critical incident technique to interview contemporary choreographers and dancers about their collaboration practices in a specific project they were working on. I probed for stories about memorable frustrating moments and rewarding ones, related to the collaboration among themselves, and with the available technology.

For each interview I collected audio, video (avoiding to shoot the interviewee's face when possible), pictures of involved artefacts, and I took written notes.

1.2.2 *Thematic analysis*

I used a thematic analysis approach (Clarke and Braun, 2014) to analyse qualitative data from various studies in this thesis. Thematic analysis is a well established method in psychology and HCI research. Similarly to grounded theory (Corbin and Strauss, 2014), it involves an iterative process in which codes and themes are crafted by the researchers to characterise the observed phenomena. However, unlike grounded theory, the objective is not to generate a theory of behaviour, but to help addressing the research questions.

I used thematic analysis to code interview excerpts, pictures, videos, sketches, and notes from observations, structured observations, and interviews with creative professionals. For each study, I first organised the data into stories. I went through the stories systematically, assigning them one or more codes, and later grouping common patterns into higher-level themes. Codes and themes were cross-checked across stories by more than one researcher[1], and disagreements were discussed until consensus was reached.

I used thematic analysis not only to interpret the collected data but also to identify opportunities for design. For example, applying the method to interviews with users of graphical editing tools resulted in a list of the key problems that users face when aligning and distributing graphical objects, which directly informed the design of *StickyLines*.

1.2.3 *Technology probes*

Based on the results from interviews with contemporary choreographers, I built a first version of *Knotation* as a technology probe, and observed how they used it in realistic settings. A technology probe is a flexible, adaptable technology that combines *"the social science goal of collecting information about the use and the users of the technology in a real-world setting, the engineering goal of field-testing the technology, and the design goal of inspiring users and designers to think of new kinds of technology to support their needs"* (Hutchinson et al., 2003).

Knotation is a pen-based mobile tool for sketching personal representations of choreographic ideas and make them interactive. I used the probe in a study with three contemporary choreographers to observe how they would use it, to spark new design directions, and to detect technical limitations, challenges, and bugs. The results lead to the identification of the main approaches participants used to express movement, constraints about movement, or both.

1.2.4 *Structured observations*

I used *structured observation* (Garcia et al., 2014) to study how participants used the prototypes I built (*StickyLines* and *Knotation*), and qualitatively compare the results. Structured observation is a quasi-experimental design (Cook and Campbell, 1979) method that proposes observing users as they perform realistic tasks in real-world settings. This enhances ecological validity while allowing researchers to identify novel user behaviour. The method combines controlled conditions to be able to detect and compare patterns across participants, using qualitative and quantitative mea-

1 Nolwenn Maudet for the studies with designers, and Sarah Fdili Alaoui for studies with choreographers.

sures. Unlike controlled experiments, it does not start from a hypothesis, but generates new, testable ones. Its use is adequate when studying complex phenomena without the goal of finding a cause-effect relationship between factors, either because these factors are still to be untangled, or because researchers are interested in answering nuanced qualitative research questions that cannot be quantified yet, or at all.

1.2.5 *Field studies*

I ran two longitudinal field studies with contemporary choreographers and dancers using *Knotation*. The first study followed a choreography course with a choreographer and a group of dancers over five months, and the second study followed a professional dance company with two contemporary choreographers and four dancers over a three-day residency. I observed participants using *Knotation* in the context of the project they were working on, which deepened our knowledge of how users use this type of technology, how it affects the social dynamics and the creative process, and what are the implications for the design of tools to support collaboration in choreography in terms of exploring and documenting ideas.

1.2.6 *Laboratory experiments*

During the development of this thesis, I had different goals that required different methodologies, as seen in the previous sections. When seeking to uncover user phenomena, I used interviews and observational studies. When in need of testing technology or probing for phenomena mediated by it, I ran technology probe studies and field studies.

After designing *StickyLines*, I needed to evaluate it as a tool for aligning and distributing graphical elements. In spite of performance not being a main factor when assessing CSTs, it is nonetheless important to show that they are not, by design, inefficient and cumbersome for users. I was specifically interested in knowing whether *StickyLines* was more efficient than the traditional commands found in most commercial systems, in terms of time and user actions. In order to test the cause-effect relationship between the alignment technique and these quantitative measures, I ran a laboratory experiment with regular users of graphical editing tools, where I only included the basic features in *StickyLines*.

The experiment did not address the tool's potential for supporting creative practice. This methodology would not be appropriate for such a purpose, since isolating creativity — which exists within a social environment and develops over time — would create an artificial setting that would fail to capture its nature. It would require an operationalisation of the concept of creativity, including a quantitative way to describe it, which would necessarily be too situational and thus not generalisable.

1.3 CONTRIBUTIONS

This thesis has three types of contributions: *technological*, *empirical*, and *theoretical*.

TECHNOLOGICAL CONTRIBUTIONS

- *StickyLines* is a graphical editor that treats guidelines as first-class objects with which users can create persistent, predictable and precise interactive alignment and distribution relationships. It introduces the concept of a *tweak*, which represents an ad-hoc spatial adjustment that the user can set for an object on a guideline, and that is maintained for subsequent interactions. It also supports the adjustment of graphical objects' bounding boxes to increase user control over the layout.

- *Knotation* is a mobile pen-based tool that lets users sketch their own representations of choreographic ideas and render them interactive. It integrates hand-drawn sketches and notes, text, images, and video. Users can compose the space, time and structure of a choreographic piece by sketching interactive floorplans and timelines. It lets them represent movement constraints and create multiple views at different levels of abstraction and keep them linked.

EMPIRICAL CONTRIBUTIONS

The following are the key findings from the nine empirical studies conducted in this thesis.

- Users of graphical editing tools would like to make the spatial relationships among graphical objects persistent, easier to control, and more general. They want to make these relationships explicit, so they can be visualised, manipulated, and captured for later editing.

- *StickyLines* supports designers who fully pre-plan the spatial structure of their layout, as well as those who progressively create and explore the structure. Designers appropriate *StickyLines*'s guidelines as semantic grouping mechanisms, beyond spatial relationships. The *StickyLines* prototype is faster and requires fewer actions than traditional alignment and distribution commands for complex layouts.

- Contemporary choreographers typically create a set of artefacts that capture their ideas, such as sketches of movement, diagrams of dancers' trajectories, video of rehearsals, etc. They rely heavily on their choreographic skills, intuition, and collective memory to map these artefacts and keep them linked.

- Contemporary choreographers have highly varied strategies for representing movement but they often seek to express constraints about it. They address the composition of a piece from different perspectives, with an emphasis in capturing movement, or constraints, or both.

- *Knotation* supports contrasting choreographic approaches (such as *dance-then-record* and *record-then-dance*). Contemporary choreographers appropriate the interactive floorplans and timelines in *Knotation* to create diverse choreographic structures. Similar to *StickyLines*, some choreographers use timelines to semantically group dance sequences beyond temporal relationships. Some appropriate their own errors to generate new ideas and discover interesting patterns, or even use *Knotation* to improvise and explore live dance fragments.

- The use of *Knotation* by contemporary choreographers and dancers in a collaborative setting reveals the need of supporting three types of collaboration: between people (negotiating), between people and technology (ideating, transitioning to refined versions), and between people through technology (transmitting material). Choreographic annotation practices are deeply influenced by the social dynamics among collaborators, especially by how agency is distributed between them. The introduction of a technology such as *Knotation* affects these dynamics and the creative process itself.

THEORETICAL CONTRIBUTIONS

- The *Choreographic Object-Operation* framework for contemporary choreography articulates the high-level patterns that emerge from contemporary choreographers' complex and idiosyncratic creative processes. The concept of *choreographic object* captures how contemporary choreographers represent their creative ideas at different levels of abstraction. A choreographic object is the object of interest of a choreographer and can refer to a specific movement, to a whole dance sequence, to the main idea for a piece, to the interaction between dancers, etc.

- The concept of *choreographic substrates* shows how contemporary choreographers can reify their creative ideas into dynamic structures that support exploration of both constraints and content. Contemporary choreographers play with creative constraints and relationships between dancers and between movements, generating and discovering patterns during the creative process. Choreographers should be able to define choreographic substrates and explore them to refine their ideas, by adding, removing, relaxing or tweaking constraints, as well as manipulating the choreographic content over time. *Knotation* facilitates the creation of spatial and temporal choreographic substrates via timelines and floorplans.

- The implications for design derived from studying collaboration in dance using *Knotation* give directions to researchers and interaction designers on how to support three types of collaboration that co-exist in this context (between people, between people and technology, and between people through technology).

- The design of *Knotation* opens a path for investigating the use of such a tool in other creative domains, e. g. interaction design, storyboarding, video prototyping. It sets a framework to explore what design principles apply to these domains and to what extent, as well as to challenge these principles and the concept of substrates.

1.4 THESIS OVERVIEW

Chapter 2 presents the theoretical context in which I frame this thesis. It includes an overview of the most relevant HCI concepts and models for this work: instrumental interaction, substrates, and co-adaptation.

Chapter 3 gives an overview of creativity in terms of its study and support. I address creativity accounts in design and in choreography, and I review the topic of creativity and constraints.

Part I encompasses the problem of studying and supporting spatial constraints in graphic design. In Chapter 4, I present an observational study with users of graphical editors about their practices and struggles when dealing with alignment and distribution. Based on the results, in Chapter 5 I introduce *StickyLines*, a tool that provides explicit representations of spatial constraints by treating guidelines as first class objects. I describe two user studies with the tool: an experiment with regular users of graphical editors, and a structured observation with designers. Finally, I discuss how the design principles used in *StickyLines* support users in defining spatial constraints.

Part II addresses the problem of studying and supporting constraints in contemporary choreography. In Chapter 6, I introduce an interview study with choreographers to examine how they capture and manage their ideas. I then propose the *Choreographic Object-Operation* theoretical framework, which attempts to capture common patterns across choreographers' idiosyncratic practices, and I list implications for design. Then, I present an observational study with choreographers and dancers about how they express their compositions without digital technology support. In Chapter 7, I tackle the definition of spatial and temporal constraints. After reviewing the relevant previous work on the exploration and documentation of choreographic ideas, and based on the findings from the two studies in Chapter 6, I introduce the design of *Knotation*. *Knotation* is a pen-based mobile tool that allows choreographers to sketch choreographic ideas and make them interactive. I describe two studies with this tool: a technology probe study with contemporary choreographers using a first version, and a structured observation of contemporary choreographers using a second version. Finally, I discuss the design principles behind *Knotation* and how they support users in defining a variety of creative constraints.

Chapter 8 explores choreographic collaboration in the wild. I study how technology mediates the creative process, and how the context affects technology use. I present two longitudinal field studies: one with a choreographer and dancers in a dance course, and one with a dance company in a residency. I propose a set of implications for design: support conflicting notation styles; leverage ludic aspects of interactive tools; facilitate transitions from drafts to final versions; combine synchronous and asynchronous communication; and let collaborators choose their own roles.

Chapter 9 reflects on the challenges of designing interactive tools to support the creative practice of designers and contemporary choreographers. It discusses how this problem can be approached by reifying users' structures through interactive substrates that articulate content and constraints.

Chapter 10 concludes this thesis with limitations and perspectives for future research.

2 CONTEXT

This chapter introduces the theoretical background that frames and influences this thesis. It explains instrumental interaction, substrates, and the phenomenon of co-adaptation between users and software tools.

2.1 INSTRUMENTAL INTERACTION

The approach I follow in this thesis for designing novel tools is directly influenced by the generative power of the instrumental interaction model (Beaudouin-Lafon, 2000). This model is inspired by our interaction with objects in the physical world, which is often mediated by tools (or instruments), e. g., pencils, screwdrivers, toothbrushes, brooms. In instrumental interaction, the objects of interest (such as documents, graphical shapes, formulas) are called domain objects, and are manipulated through interaction instruments. An interaction instrument is a computer artefact that mediates between the user and the domain objects, by turning users' actions into commands that act upon the objects.

The model proposes a change of paradigm from WIMP (*"windows, icons, menus, pointer"*) applications where interface objects that are not objects of interest (such as menus and palettes) clutter the user's workspace or add layers of indirection between the user and the objects, for example, through dialogue boxes. Instruments, instead, are first-class objects[1] decoupled from the domain objects and, ideally, from the idiosyncrasies of specific system interfaces. Such an implementation of instruments would allow them to escape the application silos, reducing the number of instruments that users need to learn to use, while making them more powerful. A recent example of this approach is seen in *Webstrates* (Klokmose et al., 2015), a web environment where users can share and edit dynamic media in real time. They can create and share their own tools to be used in different interfaces according to each user's preferences, for example, a citation tool that works seamlessly for WYSIWYG (*"what you see is what you get"*) and for plain text editors.

Beaudouin-Lafon and Mackay (2000) proposed three design principles that can be combined with instrumental interaction: *reification*, *polymorphism*, and *reuse*. Reification consists of turning

1 In programming languages, a first-class object is an entity that supports all the operations generally available to other entities.

a concept into a first-class object with which users can interact. In the context of instrumental interaction, it implies that a command is reified into an instrument. Using reification in an instrumental way helps avoiding the drawbacks of many WIMP interfaces where the user needs to navigate through blocking dialogue boxes to edit the attributes of the domain objects. Polymorphism is a property of commands that lets them be applied to different types of objects. While reification increases the potential number of objects in the interface, polymorphism decreases the number of commands that are needed to manipulate them, contributing to keeping the interface simple, yet powerful. Reuse involves providing the user with access to previous input, output, or both, so they can be partially or completely reused in the current context, rather than repeated from scratch. Polymorphism enhances input reuse as users' actions can be reapplied to a variety of contexts. Reification increases output reuse as it creates first-class objects that users can reuse.

The power of these three design principles resides in their combination. For example, the notion of a group, which implies reification and polymorphism, increases the power of the interface by enabling the user to manipulate a set of objects together, applying sequences of commands to the group rather than to each element. In summary, by reifying commands into polymorphic instruments, the users can manipulate their domain objects in rich ways and reuse their actions with less effort.

I adopted the perspective of instrumental interaction in both *StickyLines* and *Knotation*. The design of *StickyLines* (Chapter 5) in particular provided a constrained, yet rich opportunity to highlight and discuss the theoretical concepts mentioned above.

2.2 SUBSTRATES

Instrumental interaction is a descriptive, comparative, and generative model: It is useful to describe existing or new interaction techniques or systems in terms of instruments and domain objects; it provides metrics to compare them; and it facilitates the generation of novel ones. However, the model does not explicitly cover the relationships, rules, and constraints that exist between domain objects and that affect instruments, as well as the ones that are imposed by instruments themselves and affect, in turn, the objects. The ExSitu research laboratory, in which I conducted my doctoral work, has been recently exploring the scope and limitations of *substrates*, a novel theoretical concept concerning this aspect, especially in the field of creative practice.

A substrate contains information, applies constraints to it, and reacts to changes in both, generating new information. An instrument is a special substrate that can act on other substrates. A substrate can sometimes be appropriated to act as an instrument, even if not originally designed as such.

The term was introduced in the context of supporting music composition with interactive paper (Garcia et al., 2012). García et al. found that contemporary music composers make a distinction between musical content and its underlying structure: They design a variety of structures that go beyond the traditional staff, inspired by their music composition software or their own practice. A musical substrate *"captures the method by which composers create complex structures to represent their musical ideas"*, as well as *"the main properties and roles of the structures"* (Garcia, 2014). In Garcia's work, substrates are interactive components that support computation and *"act as formal representations designed by contemporary composers to explore their musical ideas while retaining great individual freedom of expression"* (Garcia, 2014). For example, in his doctoral dissertation, Garcia presents the *Tonnetz* substrate, inspired by the approach of composer Chouvel. This particular substrate uses Tonnetz — a two-dimensional network of pitches or chords — as an underlying structure that allows the composer to explore musical ideas. The substrate transforms the composer's pen strokes into melodies and chords as the composer draws a path on the printed Tonnetz (Bigo et al., 2012).

Similarly, Maudet et al. (2017) showed that graphic designers work with *graphical substrates*, which are *"the underlying structures onto which the designer grows a layout"*. The authors also defined graphical substrates as the *"principles that guide the layout but rarely appear in the final result"*. They reported on the limited support offered by current systems, and the ad-hoc mechanisms that designers use to manage their substrates manually. Among several examples, the authors tell the story of a designer who chose the number 42 and its multiples to create a layout for Douglas Adams' novel *The Hitchhiker's Guide to the Galaxy*. This required her to define and handle high-level rules to embed these numbers into the parameters that control visual elements, such as colour, font sizes, line widths and grid dimensions. Interestingly, Maudet et al. made a distinction between a *substrate* (related to the structures that the creative professional holds in their mind to guide the exploration of ideas), and a *reified substrate* (the digital operationalisation of a substrate, which is interactive and supports computation).

In Garcia's work, composers work with structures beyond the traditional staff, and the digital tools he introduces support the creation and exploration of these structures *through* substrates. The behaviour of a substrate is ultimately programmed by a developer (or a composer with programming skills) to help the composer define the specifics of the devised structures and the rules that will govern the content, in such a way that they are computable. By contrast, Maudet's approach recognises the existence of substrates beyond their digital representation. She noted that certain aspects of substrates that designers describe when interviewed about their creative practice, cannot be reified into computational systems unless they are formalised more concretely[2].

I add to García et al.'s and Maudet et al.'s contributions with findings from the choreographic creative process, where the constraints in play involve movement in time and space, as well as other humans' interpretations of these constraints.

The concept of substrates has been present from the beginning of this thesis as a generative tool that influenced my way of designing *StickyLines* and *Knotation*. For the case of choreography, I was particularly interested in how choreographers articulate the duality between structure and content, and whether they do so at all. Contemporary choreography is a field that could challenge the concept of substrates, expand our knowledge about it and push its limits, as described in Chapter 7.

2.3 CO-ADAPTATION

Together with instrumental interaction and substrates, the concept of co-adaptation forms the theoretical basis of this thesis. Mackay (1990) coined the term *co-adaptive phenomenon* to describe the relationship between users and technology. Users adapt to the available technology (they learn to use it), and they adapt it for their own needs (they appropriate it). These processes happen over time and affect each other. "*Co-adaptive*" highlights the fact that people both react to the technology, and also proactively change it.

In her doctoral dissertation, Mackay presented a longitudinal study with users of an electronic mail filter called *Information Lens*, as they customised the system, and showed that software customisation is a co-adaptive phenomenon. She argued that "*individuals are influenced by changing organizational factors, external events, and the evolution of the technology over time*", and noted that they "*may also share patterns of use, creating socially-defined norms of behavior that may ultimately affect the structure of the organiza-*

2 While writing this dissertation, I had a chat conversation with Maudet about this aspect. She stated: *"I don't go too far into describing the 'substrates' that they have in their minds, because I'm very pragmatist (Schön, Ingold...) and it's really hard to know how 'defined' these substrates are in the mind. Sometimes, it may be that it's because I asked them in the interview, that they were able to [make] explicit these substrates, really. But what is clear is that once it's reified into a system, it is a 'determined' and 'complete' object and it leaves no space to an ambiguity that is always there in [the] thoughts, hence a difference in nature"*. (Nolwenn Maudet, 2018, personal communication)

tion" (Mackay, 1990). Around this time, other researchers identified similar user behaviour in the context of sharing customisations of spreadsheets (Nardi and Miller, 1991) and *NoteCards* (Trigg et al., 1987)[3].

Later, Mackay (2000a) postulated that designing with co-adaptation in mind can help users coping with cognitive overload in their work environment as it becomes more complex. She presented a user study with the staff of the MIT's Project Athena, as they learnt to use a new technology (the X-Window system) and customised it over time. She found that the users were influenced by the design, implementation and use of the technology in their work environment, and that they appropriated it in ways that the designers had not anticipated.

In this context, Mackay proposed three specific design considerations to reduce cognitive overload: *Reflection* (give users feedback about the effectiveness of their actions, and opportunities for reflecting on that); *Context* (let users capture and customise their work context and patterns of behaviour); and *Sharing* (enable users to share their customisations).

In summary, Mackay suggested to ground technology design in existing, successful work practices, and then seek to augment these practices through technology while the user retains control. It is key to bear in mind that the user will interact with the technology over time, and that from the user's perspective there is no distinction between adapting to the technology and adapting it: The user tries to get a task done, using the technology in such a way that helps them achieving their goal.

2.4 SUMMARY

This chapter described the theoretical background that frames this thesis and influences my approach to designing technology for creative professionals. Instrumental interaction proposes to reify commands into polymorphic instruments, so that users can manipulate their domain objects in rich ways and reuse their actions with less effort. Substrates complete the scene by embedding the relationships between domain objects into the technology, and by making them interactive. The interaction between users and technology requires to recognise and support co-adaptation, helping users to learn such technology and appropriate it for their own needs.

3 *NoteCards* was a hypertext-based idea structuring system aimed at designers, authors, and other knowledge workers. It supported users in *"collecting, representing, managing, interrelating, and communicating ideas"* (Halasz, 1988).

3 CREATIVITY

This chapter gives an overview of creativity research. It includes the most prominent empirical and theoretical contributions in the literature, as well as attempts to support and enhance creativity. Then it addresses creativity accounts in design and in choreography in particular, and finishes with creativity constraints, with a focus on these two disciplines.

Creativity has been present in the writings of Western philosophers since the time of Ancient Greece. As described by Rothenberg and Hausman (1976), Plato argued for its *"inexplicable, mysterious basis"*, while Aristotle believed that creative processes followed natural laws. However, the scientific research on creativity did not start until research itself was recognised as a method for understanding the world (Runco and Albert, 2010). Even then, the ongoing mystification of creativity is likely to have prevented many scientists from studying it (Plucker et al., 2004; Sternberg, 2003).

The definition of creativity has been an object of discussion in psychology and creativity research since before the twentieth century. From the numerous definitions in the literature, Runco and Jaeger (2012) highlighted the need for *originality* (novelty, uniqueness) and *effectiveness* (usefulness, fitness) for something to be creative. The definition proposed by Plucker, Beghetto and Dow (2004) meets these requirements while capturing the social and situated nature of the concept: *"Creativity is the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context"*.

However, I agree with Morris Stein (1953), in that a distinction between the *creative product* and the *creative experience* must be made. Stein warned that neglecting the creative experience, which is subjective by nature, can lead to a limited view of creative phenomena. This argument resonates with Margaret Boden's (2004) division of creativity into *psychological (P-creativity)* and *historical (H-creativity)*. P-creativity refers to an idea that is novel to the person who has it, while H-creativity involves an idea that has never emerged in history before. For Boden, P-creativity is fundamental for understanding the *"psychology of creativity"*, and in particular how a person manages to make an idea arise. Even though some P-creative ideas could be in contradiction with Plucker et al.'s definition of creativity, I consider them as an important part of the creative experience, and I see the creative process of each practitioner as a fundamental source for design.

Defining creativity is problematic as it raises both the matter of *what* is creative, and *who* decides so. Csikszentmihalyi's (1988) reframing of the question *"what is creativity?"* to *"where is creativity?"* helps to some extent. He went beyond the view of creativity as an inherent attribute of a product, and argued that there are three interacting components responsible for creativity judgements: 1) the domain (body of knowledge in a discipline at a certain time); 2) the field (experts in the discipline); and 3) the person (the creator). According to Csikszentmihalyi, *"each has a say in what counts as creative"*, but *"the attribution of creativity is not a democratic process"*. He talked about the existence of *"gatekeepers"*, an elite within each field with a privileged role of power; for example, in the case of art, the gatekeepers would be museum curators, gallery owners and collectors.

Given that even the notions of domain and field are still subjects of debate, in this thesis I recruited study participants who self-define as *designers*, *choreographers*, or *dancers*, and I purposely avoided judging the creativity in their processes or their products, seeking to incorporate their voices whenever possible.

3.1 STUDYING CREATIVITY

On top of definitional issues, studying creativity is difficult because the associated cognitive processes are fast and elusive, and an idea may be identified as creative post-facto, which makes capturing creativity in a controlled setting a challenging endeavour (Stevens et al., 2003).

EMPIRICAL PERSPECTIVE

First steps: The demystification of creativity

During the Enlightenment, scientists became interested in the topic of creativity[1], in particular regarding the extent to which creativity demanded *"superior intelligence"* (Simonton, 2000). In the nineteenth century, Francis Galton's (1883) assessment of creativity contributed to demonstrate — maybe against his own expectations — that *"genius"* did not have a supernatural origin, and that creative ability was distributed throughout populations (Runco and Albert, 2010), influencing the research on creativity of the next decades. Wallas (1926) proposed a creative process consisting of an ordered sequence of stages, discredited later when the

1 See Runco and Albert (2010), for a comprehensive review.

field demonstrated the complex, non-linear nature of the process. The most prominent investigations before World War II are perhaps Catharine Cox's (1926). Combined with the development of ego psychology, her studies helped unlink creativity from psychopathologies and antisocial behaviour, and showing that creativity was not merely unconscious (Runco and Albert, 2010). Another fundamental finding from this period is that over a threshold, there is minimal relation between intelligence and creativity (Barron and Harrington, 1981).

Creativity in the individual: The study of creative people's traits

Although many of the most well-known psychologists of the twentieth century (e. g., Freud, Piaget, Rogers, Skinner) explored creativity and what it means to be creative, it was Guilford's presidential address to the American Psychological Association that marked an inflexion point in creativity research (Runco and Albert, 2010). He urged psychologists to study creativity, with the goals of *"selecting the individuals with creative potentialities"* and increasing their abilities (Guilford, 1950).

Until the 1970s, psychometric approaches based on pencil and paper tested participants in terms of divergent thinking[2] and the originality of their responses (Burnard, 2007), with the goal of using creative thinking as a predictor of *"human capacity"* (Sullivan, 2007). Along these lines, psychologists addressed the study of creativity from the perspectives of individual problem-solving (Duncker and Lees, 1945; Maier, 1945; Wertheimer, 1945) and personality and thinking processes (Ghiselin, 1963; Hallman, 1963; Torrance, 1962). The emphasis was often put in comparing exceptionally creative people with more *"average"* individuals (MacKinnon, 1962, 1963; Roe, 1953). As stated by Runco and Albert (2010), creative people became Western *"culture's heroes"*.

Creativity beyond the individual: The study of external influences

Over the next decades, researchers understood that the view of creative behaviour as composed of discrete human abilities was a narrow one (Sullivan, 2007). As described by Watson et al. (2012), the myth of the *"lone genius"* started to be dismantled by researchers who uncovered a *"web of support, inspiration and knowledge exchange"* behind innovations and art works of individuals (see, e. g., Csikszentmihalyi, 1996 and John-Steiner, 2000). The field moved beyond *what* is creativity, which as described by

2 Divergent thinking *"allows one to explore in different directions from the initial problem state, in order to discover many possible ideas and idea combinations that may serve as solutions"* (Finke et al., 1992).

Sullivan (2007), was *"seen as a biological construct or a desirable disposition of the mind"*, and started to ask *when* and *where* creativity unfolds (Csikszentmihalyi, 1988), considering its contextual, emotional, political, and sociocultural aspects.

Torrance (1979) was one of the first in going beyond personality approaches. Others contributed with findings regarding the influence of the environment in creativity and innovation (Amabile, 1983; Amabile and Conti, 1999; Amabile et al., 2004; Tighe et al., 2003), and the importance of the domain (Csikszentmihalyi, 1994; Gardner, 1983; Moneta, 1993). Although comparisons between extremely creative individuals and *"average"* ones continued taking place, they were approached in a more humane way. For example, Dudek and Hall (1991) described both types of participants respectfully and in depth, in contrast with some earlier studies that exaggerated the gap between them.

Cognitive processes and training: The further demystification of creativity

In the 1990s, findings in the cognitive understanding of creativity helped with its further demystification. Finke et al.'s (1992) experimental studies using open-ended problems demonstrated the role of visual imagery in the birth of creative ideas. This approach, called creative cognition, showed that creative discoveries can arise from the *"systematic implementation of ordinary cognitive processes"* (Ward and Finke, 1995), and thus are accessible to anyone (Simonton, 2000).

Others (Gardner, 2011; Hayes, 2013; Simonton, 1991) showed that creativity requires training and practice, and that world-class professionals' creative ideas often come from the accumulation of refined skills and domain-related knowledge (Simonton, 2000), contradicting the popular belief in creative genius as a quality with which people are born.

Creativity as a systemic phenomenon: The methodological shift

Once researchers understood that creativity was a systemic rather than an individual phenomenon, it became harder to study it with the classical methods in psychology (Simonton, 2000). Some, such as Martindale (1990), used archival data to analyse the interaction between creators and their disciplines, and others employed some form of participant observation (e. g., Dunbar's observations in biomedical laboratories, 1995). The field also made a more comprehensive use of the case study method (Gardner, 2011, first published in 1993; Wallace and Gruber, 1992; Weisberg, 1993), cross-cultural inquiries (Lubart, 2010), biographical, auto-biographical, and historical approaches (Gruber, 1981; Simonton, 1999; Smith and Watson, 2002), auto-ethnography (Reed-Danahay, 1997), and a/r/tography (Irwin and De Cosson, 2004).

An interesting example is that of Gruber et al. (1989), who analysed archival sources such as lab notebooks, diaries, and sketchbooks, to study the emergence and development of creative ideas, taking into account the interplay between the creator's vision and their sociocultural context. Simonton (2000) noted that, as in Wallace and Gruber (1992), a salient characteristic of these two works is their emphasis on the case study method, a qualitative approach that allows *"an in-depth understanding of how creativity works in individual lives"*.

More recently, researchers have analysed the potential of collaborative or distributed creativity (see, e. g., Glăveanu, 2014; Miettinen, 2006; Sawyer, 2007; 2011) and the combination of individual and social creativity (Fischer et al., 2005; Halskov and Dalsgaard, 2007). From a methodological point of view, scientists in psychology and HCI have argued that in order to grasp its complexity, creativity should be studied in real world settings rather than in laboratory experiments (Frich et al., 2018b; Simonton, 2003; Wiltschnig and Onarheim, 2010). Although it was noted by Simonton (2000) almost two decades ago, we still lack a deep understanding of creativity in women and minorities (see for example Helson, 1990), as well as more longitudinal studies that follow the development of creativity during childhood, adolescence, and adulthood.

THEORETICAL PERSPECTIVE

Early theories of creativity were unidimensional and failed at capturing its complexity. Starting in the 1960s, multidimensional theories and models emerged, e. g., Guilford's (1967) structure-of-intellect model, Sternberg's (1985) theory of intelligence, and Gardner's (1983) theory of multiple intelligences. Gardner's theory is particularly interesting — and provocative — as it includes abilities such as musical, bodily-kinaesthetic, interpersonal, and intrapersonal intelligences, and each is associated with a type of creative expression, e. g., painting, choreography, or psychology (Gardner, 2011).

The *Cambridge Handbook of Creativity* (Kaufman and Sternberg, 2010) has a chapter entirely dedicated to theories and models of creativity, organised into ten categories (Kozbelt et al., 2010). In it, Kozbelt et al. analysed the theories according to the aspect of creativity that they emphasise. In the traditional *"4 P's of creativity"* framework, the aspects are: *process*, *product*, *person*, and *place*. More recently, two *P's* were added: *persuasion* (Simonton, 1990) and *potential* (Runco, 2003).

Kozbelt et al. also argued that in order to compare the theories, it is useful to distinguish between *little-c* and *Big-c* creativity. Big-C involves eminent examples of creative expression (e. g., Frida Kahlo's paintings, John Coltrane's jazz, Marie Skłodowska Curie's research). Little-c refers to creativity in everyday life (Richards, 2007), for example, coming up with a new hairstyle, an imaginative solution for a scheduling problem at work, or a novel way to cook a traditional recipe.

The dichotomy between little-c and Big-C ignores complex nuances within and across these categories, carrying the risk of judging non-eminent but sophisticated creative work as little-c. For this reason, Kaufman and Beghetto (2008; 2009) proposed the addition of two categories: *mini-c* and *Pro-c*. Mini-c represents the creativity inherent in a learning process, and it encompasses the *"novel and personally meaningful interpretation of experiences, actions, and events"*. Mini-C instances are likely to be examples of Boden's psychological creativity, and may not fit Plucker et al.'s (2004) definition of creativity discussed above, which puts in evidence, once more, the difficulty in defining creativity in all its levels and nuance. Pro-c refers to the creativity of professional creators (e. g., artists, designers, scientists), who have not reached eminent status but are beyond little-c creators in terms of expertise and intentions.

In this thesis, I am interested in designing interactive tools for Pro-c creativity, supporting the expert creative practice of professionals. In the 4 P's framework terminology, I put the emphasis in supporting the *process* that leads to the creation of a *product*, and I probe into this process as experienced and recalled by the *person*, i. e. the creative professional or group of professionals involved.

In the next subsections I briefly describe two influential concepts in creativity research and in this thesis: situated action and distributed cognition.

Situated action

Although greatly overlooked in reviews of creativity research, a highly relevant concept is Lucy Suchman's *situated action*. She introduced concepts from anthropology to cognitive science and artificial intelligence (AI), revolutionising the perspective of both communities (Adelson, 2003b). Before situated action, AI researchers focused on rule-based systems, seeking to embed into interactive systems the users' plans to solve problems (Adelson, 2003a). Suchman demonstrated that problem-solving cannot be reduced to the application of a plan, as plans are resources for action (Suchman, 1987). Plans aid people to decide what aspects of the environment should be considered in order to achieve their goals. Through her observations, Suchman revealed the creative and improvisational abilities that people put in practice daily in the workplace. She recommended that systems should support this human creativity by matching the context-driven nature of users' interaction with technology (Adelson, 2003a).

Situated action contributed to understanding people as members of social, cultural, and material configurations (Adelson, 2003b). It created awareness of the role of the environment in human actions, and the importance of context in cognition. Suchman saw individuals as entities in a network of relationships, from which effects emerge. She reframed design as a distributed social accomplishment in which artefacts and other people play key roles (Kimbell, 2011).

Distributed cognition

Another influential theory is *distributed cognition*, popularised in HCI by Hollan et al. (2000). It is both an attempt of understanding interactions among people and technologies, and a framework for the design and evaluation of digital artefacts. It widens the scope of what is considered *cognitive* beyond an individual, to reach interactions between people and with resources in the environment. As an individual is a component of a complex cultural environment, culture shapes cognitive processes, which are socially distributed across the members of a group. Distributed cognition includes, then, phenomena that emerge in social interactions, as well as interactions between people and external structures, for example, objects and representations of objects.

A fundamental principle in this theory is that people *"off-load cognitive effort to the environment whenever practical"*, as they constantly create and coordinate *"external scaffolding"* to simplify cognitive tasks (Hollan et al., 2000). Hollan et al. argued that the *"physical environment of thinking"* plays a role that goes beyond merely providing additional memory: It offers opportunities to reorganise the distributed cognitive systems. The environment can be seen as a pool of resources for learning, problem solving, and reasoning, where the meanings of the actions are grounded in the context of the activity. According to the authors, *"work materials become integrated into the way people think, see, and control activities"*. Like Suchman, Hollan et al. suggested HCI researchers to consider tasks in a *"complex networked world of information and computer-mediated interactions"*.

Similarly, Press and Warburton (2007) highlighted the idea of physically distributed development, which defines creativity in a *"physically, socially, and symbolically distributed world"*, encompassing the diversity of current perspectives on creativity. Although the distributed cognition theory does not explicitly address creativity, it is highly applicable to both individual and collaborative creative processes, as cognition is distributed across the creators' minds and the artefacts they generate, for example, sketches in design and videos or scores in choreography.

3.2 SUPPORTING CREATIVITY

Psychologists are responsible for most of the studies and theoretical contributions in the field of creativity, but their discipline is not directly concerned with its support and enhancement.

CREATIVITY ENHANCEMENT TECHNIQUES

A variety of techniques have been developed in the business world for fostering the creativity of individuals and teams, for example, De Bono's lateral thinking (1971), Osborn's brainstorming technique (1953), and Gordon's synetics method (1961). In 2000, Shneiderman mentioned De Bono's lateral thinking as an example of the methods promoted by *inspirationalists*: Writers that "*talk about gifted individuals, but usually stress that creativity-inducing thought processes can be taught*" (Shneiderman, 2000). Sternberg (2003) explicitly critiqued these techniques, which according to him "*lack any basis in serious psychological theory nor have there been serious empirical attempts to validate them*". However, Sternberg recognised that they may be useful, and that "*techniques can work in the absence of psychological theory or validation*" (Sternberg, 2003).

CREATIVITY-SUPPORT TOOLS

Mainstream HCI, addressing mostly productivity, usability, and computation, did not play a major role in supporting creativity until the 1990s. In fact, Gerhard Fischer (1993) stated that until then, systems had "*restricted rather than enhanced creativity*", even though "*computers ha[d] the potential to be creativity enhancing tools*". By the end of that decade, the *Creativity & Cognition* conference, created in 1993, had already seen a shift from the automation to the augmentation of creativity (Candy and Edmonds, 1999).

Designing CSTs

HCI researchers proposed concrete design guidelines for the development of CSTs, which can be defined as "*any tool that can be used by people in the open-ended creation of new artefacts*"

(Cherry and Latulipe, 2014). Shneiderman (2000) described three approaches to creativity that could be combined in the design of CSTs: *inspirationalist*, *structuralist*, and *situationalist*. For example, systems could foster inspiration by allowing creators to access and reflect on previous work; they could provide structured tools that enable exhaustive exploration; and they could facilitate collaboration and communication, to support the situationalists' strategies.

As a result of a workshop on this topic (Shneiderman et al., 2006), Resnick et al. (2005) provided a set of 11 design principles. Later (2007), Shneiderman added to these principles, arguing that CSTs should facilitate exploratory search, support generation of multiple alternatives, enable collaboration, provide a rich history, and allow users to revert to previous states as needed. Along the same lines, Hewett et al. (2005) suggested that researchers must first observe the creative practice, identify problems to address, and then design prototypes before proposing an actual solution. This should be followed by qualitative and quantitative studies that compare the novel tools with the existing practices.

Evaluating CSTs

Resnick et al. (2005) signalled the difficulties in assessing the extent to which a CST fosters creative thinking. In this direction, they posed longitudinal studies with "*active users*" as a valid method to identify what is helpful and why. Examples are Shneiderman and Plaisant's (2006) longitudinal case studies with expert users of information visualization tools. Other qualitative methods can be found in the literature. For example, Kerne and Koh's (2007) work on information composition in a creativity course applied grounded theory (Corbin and Strauss, 2014) over case studies. Höök et al. (2003) designed a qualitative methodology to evaluate the creative product of an artistic activity involving an interactive installation. They pointed out that when carrying out a project that combines art and HCI, possible mismatches between these two communities need to be considered. Given that art is inherently subjective, and that HCI traditionally tries to be objective, artists and researchers must sensibly negotiate their goals and methodologies. The authors proposed to adapt HCI evaluation methods, such as user testing, to help artists fine-tune interactive artwork. They suggested that the perspective of artists, in turn, can benefit HCI by revealing novel aspects of the relationships between system designers, users, and evaluators.

Regarding quantitative methods, the most well-known is Cherry[3] et al.'s (2009) *Creativity-Support Index* (CSI), a psychomet-

3 Formerly Carroll.

rically validated survey tool for complementing the evaluation of CSTs. The structure of the survey, inspired by the NASA TLX, involves agreement statements about the tools, that participants rate using Likert-like scales. The method does not intend to measure all the aspects of creativity but rather focuses on six orthogonal factors: results worth effort, expressiveness, exploration, immersion, collaboration, and enjoyment. The score in each factor allows designers to identify which aspects of their CSTs need attention. Cherry and Latulipe (2014) suggested reporting the final score with the task and the level of expertise of each participant, both in the domain and with the CSTs being tested. They also proposed possible scenarios where the CSI could be used, e. g., to assess an individual tool for one or several tasks, to compare several tools (within or between participants), in short or long-term studies.

Researchers in HCI have also explored the quantitative study of creativity with the goal of informing the design of future CSTs. For example, Kerne et al. (2008) published an experimental method to measure the emergence of new ideas in information discovery tasks; Webb and Kerne (2011) proposed metrics to quantify the fluency, novelty, and variety of ideas in information-based ideation tasks; and Kerne et al. (2014) later refined a quantitative methodology for evaluating information-based ideation support tools through elemental and holistic metrics.

Cherry and Latulipe (2012) explored the concept of *"in the moment"* creativity (ITMC), as a step towards identifying which factors hinder or harness creativity. This would help researchers designing CSTs that keep people in a state of flow, and that enhance their creative process and experience. The method aimed at detecting a correlate of creativity based on the *"temporal representation"* of the creative experience, instead of producing a quantified, comprehensive metric of creativity. In order to measure this temporal representation, they used a triangulation of metrics: self-report techniques, external judges, and physiological sensors. Eleven participants sketched for 30 minutes with a digital tool on a graphics tablet, while wearing EEG sensors. Then participants were shown a video of the task and reported the moments when they were being creative. The judges also watched the videos and did the same reporting. The authors found high reliability for self-reporting ITMC, some agreement between participants and judges (as the judges could not know what participants were thinking and feeling), and that both were comfortable reporting the ITMC. Participants' past creative behaviours were assessed with the *Creative Behavior Inventory* (Hocevar, 1980), and classified in two groups based on their score. Results suggest that during high creativity periods, highly creative participants had significantly lower cortical arousal than the less creative participants. The authors recommended the combination of EEG and self-reports as the less expensive option, and proposed possible uses of ITMC detection, e. g., getting the user in or out of creative peaks, designing adaptive interfaces that engage users in the creative experience, and quantifying contextual effects on the creative experience while using a CST.

3.3 CREATIVITY IN DESIGN

STUDYING CREATIVITY IN DESIGN

Scholars from several disciplines such as philosophy, psychology, and HCI, have studied creativity in design for the past five decades. Fischer (1993) posed design as *"one of the most promising activities to study creativity"* , because several designers facing the same problem are likely to generate different solutions (Jacob, 1977); good designers often break the rules; design involves ill-structured (Simon, 1973) and wicked problems[4] (Rittel, 1972); and design lacks optimal solutions and always implies trade-offs. Seminal works include Simon's books on the nature of design (1996, first edited in 1969) and on design as problem-solving (1973), Schön's studies of creative practitioners (1983; 1987), and Lawson's work with architects and designers (2006, first edited in 1980). Simon conceptualised design as a rational problem-solving activity where the designer searches within a design space of possible solutions. Schön advocated for the importance of problem setting, as opposed to just problem solving. In this context, he argued that *"competent practitioners usually know more than they can say"* (Schön, 1983), as they design using implicit knowledge gathered from previous experience. Practitioners make use of this tacit knowledge through *knowing-in-action* (which assumes that knowledge is *in* the action being performed) and *reflection-in-action* (which implies reflecting about the action performed while it is still happening). For Schön, *"artistry"* can be described, however: *"When practitioners reflect-in-action, they describe their own intuitive understandings. And it is possible to describe reflection-in-action itself (...) It is true, nevertheless, that there is always a gap between such descriptions and the reality to which they refer. When a practitioner displays artistry, his intuitive knowing is always richer in information than any description of it"* (Schön, 1983).

4 Defined by Fischer (1993) as *"intrinsically open-ended, situation specific and controversial"*.

Co-evolution of problem and solution

Some works focused on the process of refining a design problem and its solution, rather than on the "aha moments" typically associated with a creative leap. For example, in his studies of designers, Cross (1997) described creative design as an exploration, rather than as a search, stating that *"creative insight in design should be regarded as a perceptual bridge-building between problem and solution, rather than a leap"*. He also discussed challenges in the devising of computational systems for creative design, with a focus on modelling the creative activity.

Later, Dorst and Cross (2001) conducted experiments with industrial designers that showed how problem and solution co-evolve during the design process, confirming the bridge-building nature of matching problem-solution pairs[5]. They noted that although studying creative design is challenging because *"there can be no guarantee that a creative 'event' will occur during a design process"*, creativity can be found in every design project. They warned, however, that *"'creative design' is not necessarily 'good' design"*, and that from the designer's perspective, the goal is normally to produce a high-quality design, with creativity being only one aspect of a design concept. They also observed that designers choose what to do when, based on how they perceive the design task, including the design problem and situation, the resources, and their own goals; and argued that these factors affect the creativity of the resulting design.

Use of tools and resources

Another topic of interest has been designers' use of analogue and digital tools and cognitive resources, mostly from a pragmatic approach. One of the main contributions is Peter Dalsgaard's (2017) *instruments of inquiry*, a conceptualisation of tools in design that supports creativity and exploration by scaffolding the process of inquiry[6]. These instruments (perception, conception, externalization, knowing-through-action and mediation) complement designers' abilities and aid their perception and understanding of design problems and their solutions. Dalsgaard argued that it is key for designers to master specific types of instruments, which open new paths for exploring the world. A related example is Gedenryd's (1998) work, who studied cognition in design with an emphasis on sketching, and proposed the concept of *interac-*

5 The term co-evolution should not be confused with Mackay's (1990) *co-adaptation*.

6 Biskjaer and Dalsgaard (2012) defined inquiry as *"the mode of action and thinking by which we identify problematic aspects in our surroundings and intentionally strive to transform them"*.

tive cognition, which refers to the distributed process of designerly inquiry.

Collaborative and social aspects

Fischer (1999b) claimed that in domains such as design, achieving expertise takes more than a decade, and as a result specialisation increases and collaboration is required. In this context, practitioners need *"reference aids, such as printed and computational media supporting external cognition"*. Fischer emphasised *boundary objects* as means of supporting social creativity in design[7]. Fischer viewed externalisations of knowledge as boundary objects that could facilitate shared understandings and communication, in order to create new knowledge. More recently, Inie and Dalsgaard (2017a) surveyed interaction designers about their use of tools to capture, manage and collaborate on design ideas. They found that designers use a wide variety of digital services and mobile devices, but still prefer analogue tools for collaboration. Their results suggest that available tools could enhance the personalisation of designers' work practices.

SUPPORTING CREATIVITY IN DESIGN

Designing CSTs for design

HCI researchers have also contributed with the design of CSTs to support creativity in design. Examples include: building domain-oriented design environments for individual and social creativity (Fischer, 1999a); addressing the design process as a collaborative activity (Arias et al., 2000); focusing on individual, sub-group and group design tasks (Streitz et al., 1999); and supporting individual and shared spaces (Sugimoto et al., 2004). In the particular cases of graphic and interaction design, a review of design software can be found in Nolwenn Maudet's doctoral dissertation (2017). She organised design software applications in three waves: research (originated from computer scientists' explorations, e. g., Sketchpad, by Sutherland, 1964); industry (seeking to replace traditional graphic design tools and get integrated in designers' workflows, e. g., Aldus' PageMaker, Adobe's InDesign); and design (created by graphic designers, generally trying to reinvent the field, e. g., Processing, 2009). Maudet studied designers' creative processes

7 For example, in the context of a Natural History museum, some boundary objects might be maps, specimens, and field notes. These are used in fundamentally different ways by amateur collectors, conservationists, museum authorities, and professional biologists. Boundary objects *"inhabit several communities of practice and satisfy the informational requirements of each of them"* (Star, 1989).

and developed a set of tools that leverage their existing practices and decouple structure and content (Maudet et al., 2017). I am inspired by this work, but I focus on the specific case of alignment and distribution, and in the more general case of contemporary choreography.

Evaluating CSTs for design

Multiple researchers offered specific methods to evaluate how tools and environments contribute to creativity in design. For example, Bonnardel and Zenasni (2010) ran three studies with designers using CAD (computer-aided design) systems, in order to understand the impact of technology in creativity. Analysing their results from a cognitive perspective, they found that the systems contributed to the divergent (generating multiple solutions to a problem) and convergent (deducing a specific solution to a problem) processes underlying creativity, helping designers generate and assess creative ideas. Kim and Maher (2005) compared designers' use of a GUI (graphical user interface) and a TUI (tangible user interface) in a collaborative design task. Their results suggest that their TUI encourages the revision of previous design decisions; sparks the discovery of unexpected spaces or features; and improves the designers' spatial cognition. Landay and Myers (2001) built the *SILK* system, in which designers can sketch user interface components (e. g., sliders, buttons) using a pen or a mouse. They evaluated the potential of the system for supporting creativity by assessing it in terms of how many ideas were designers able to work with simultaneously; how varied where the components they used; and how effective the electronic sketches were for communicating design ideas to collaborators (Landay, 1996). Resnick et al. (2005) argued that these factors do not reveal the quality of users' designs, which remains an open question in HCI, and one beyond the scope of this thesis.

3.4 CREATIVITY IN CHOREOGRAPHY

The Western choreographic tradition of prescribed movements and step patterns, such as those in classical ballet or ballroom dance, offered little room for choreographers to define their own aesthetics and style (Hagood and Kahlich, 2007). It was not until the twentieth century when personal vision was consolidated for the first time in dance making.

The role of creativity in choreography evolved in the realms of choreographic practice, education, and research. Modern dance artist Isadora Duncan saw ballet vocabularies as imposing *"artificial mechanical movement not worthy of the soul"* (Duncan, 1996, first published in 1927). Performing with hair loose, bare feet, and free flowing garments (Fig. 3) to the music of Beethoven, Mozart, Chopin, Wagner — which had been regarded as being *"above dance"* — she revolutionised dance tradition[8]. Duncan insisted on the definition of a personal approach to dance, and inspired other artists to find their own ways of making movement, which shaped the field of modern dance (Blom and Chaplin, 1982; Press and Warburton, 2007). Martha Graham, another influential dance artist, established modern dance as a serious art form, based on her connection with the modern art and architecture of the 1930s and 1940s in the United States (Giguere, 2013). Graham believed that training gave dancers freedom to express the choreographer's emotions and ideas. In 1928, her collaborator Louis Horst composed the music for her piece *Fragments*, breaking free from the prevalent tradition of having dance composed to an existing piece of music. Duncan and Graham both challenged the expectations and obstacles of a creative world dominated by men (Gardner, 2011). Duncan, Graham, and other artists such as Ruth St. Denis, Ted Shawn, Doris Humphrey, Charles Weidman, viewed creativity in dance as an expression of *"embodied meaningful human existence"* that went beyond the beauty of its external manifestation (Press and Warburton, 2007). Modern artists introduced themes such as modern life, social justice, and the relationship between men and women (Gardner, 2011).

Figure 3: Isadora Duncan. Source: Genthe, A. Library of Congress, https://www.loc.gov/item/agc1996000010/PP/

In parallel, the most influential ballet choreographer of the twentieth century, George Balanchine, fused classical ballet ideas with modern concepts, changing the history of ballet and influencing the work of famous choreographers that came after, e. g., Jérôme Robins, Alexei Ratmansky, and Benjamin Millepied. His technique emphasised extreme speed and line, and unconventional hand placement. He broke away from narrative ballet and created pieces with simple themes and modern music that were regarded as original and imaginative[9].

In pedagogy, Margaret H'Doubler — a pioneer in encouraging children to create their own movements — employed dance to foster creativity, stressing the kinaesthetic sense and the understanding of the body in motion (Press and Warburton, 2007). She sought to develop dance as a science and as an art (Morris, 2005).

Modern dance artists and educators were influenced by the work of dance theorist Rudolf Laban (1948; 1956), whose analytic frameworks, Labanotation and Laban Movement Analysis

8 Source: Isadora Duncan's biography, available at: http://www.duncandancers.com/about.html, accessed on August 7, 2018.

9 Source: George Balanchine's biography, available at: http://balanchine.org/balanchine/01/bio.html, accessed on August 7, 2018.

(LMA), served as a basis for creativity research in dance[10]. In the 1960s, the concept of what constitutes creativity in dance widened beyond technical expertise in order to include everyday life moments (Press and Warburton, 2007). Non-literal dance flourished with Merce Cunningham, one of the biggest names in contemporary dance, whose work was influenced by Laban's theories (Schiphorst and Cunningham, 1997). He revolutionised the art by, for example, choreographing pieces independently from music: Sometimes the dancers would hear it for the first time in performance (Giguere, 2013). For Cunningham, the subject of the dance was dance itself, and not an emotional state or a visualisation of music. He collaborated with avant-garde composer John Cage, exploring the use of electronic equipment and computers, and incorporated chance methods to his choreographies — sometimes allowing the audience to decide the order of the sections — as a way of deviating from his habitual ways of moving. Cunningham also decentralised space, so that all the parts of the stage were equally important and the dancers' use of space was unpredictable.

STUDYING CREATIVITY IN CHOREOGRAPHY

Individual accounts

In their review of the literature in creativity research in dance, Press and Warburton (2007) highlighted the deep personal nature of the investigations that dominated the field up to the 1980s: mostly descriptive individual accounts of the creative experience that detailed *"what it feels like to dance, to be creative, and to teach dance"*, often with informal methodologies or anecdotal evidence. John Morris (2005) argued that collections of interviews with dance artists about their creative processes and products gave more space to comparisons than individual autobiographies, and mentioned dance criticism as another form of early research.

Wendy Oliver (1992) noted that by the 1960s, the lack of systematic research in dance had became a real concern. It was still unclear how to grow an academic approach out of autobiographical accounts, in order to provide deeper and more generalisable analyses about the choreographic creative process (Hagood and Kahlich, 2007). On top of this, many dancers, choreographers, critics, and historians resisted theoretical considerations of dance (Copeland and Cohen, 1983).

One exception is modern dancer Doris Humphrey's (1959) seminal book, which promoted a systematic view of choreography as

10 John Morris described LMA as *"a system for analysing movement characteristics and capabilities, including the expressive aspects of movement"* (Morris, 2005).

a craft, influencing educators and the general public for many years. Despite Margery Turner's (1963) lack of detail, Hagood and Kahlich (2007) argued that her work offered one of the first methodologies for collecting and organising data in the context of choreography research.

Examining and improving the creative process

Starting in the 1980s, researchers adopted a more systematic approach, with formal methods and interdisciplinary efforts to capture the choreographic creative process in terms of creative choice and creative abilities. For example, Blom and Chaplin (1982) addressed the complete choreographic creative process, providing advice about techniques and artistic concerns for beginning and advanced choreographers and dance students. Ann Green Gilbert (1992) emphasised the importance of dance problem-solving and training in the creative process. Penelope Hanstein's (1986) dissertation offered a philosophical perspective about the nature of the choreographic process, its relation with the choreographic product, with the audience, and the characteristics of dance as a medium with which the choreographer interacts. She also argued for the training of creative thinking abilities (such as problem finding, transforming, and solving) in order to create inventive works of art.

The field was also concerned with the development and teaching of dance composition *"best practices"* (Hagood and Kahlich, 2007). Some researchers proposed dance education models that involved conceptual frameworks for the creation, evaluation, and performance of dance, advocating for a conceptual approach as the key to improve the creative process (Press and Warburton, 2007). Preston-Dunlop (1980) applied Laban's ideas to creative dance pedagogy; Smith-Autard (2000) published a textbook on dance composition targeting students and dance teachers, and produced a CD-ROM with resources for exploratory creative activity in dance (Smith-Autard, 2003), one of the first to use multimedia in that context. Crawford (1992) compared the literature in choreography, music composition, and painting, and identified a set of common organisation principles, such as unity, variety, contrast, and balance. He proposed additional principles for dance education, including coherence, dynamism, repetition, rhythm, emergence, and development. Press (1991; 2002) examined a psychology of creativity in dance, including the motivation behind dance-making and the impact of the maker's feelings. She applied this self-psychology to the teaching of choreographic practices, showing the relational nature of the creative process (Press and Warburton, 2007). In this period, documentaries about the creative process of famous choreographers were produced and distributed[11].

Researchers also tried to assess the creativity and personality traits of dancers, in relation with non-dancer populations. For example, Alter (1984) compared dance students with art students and non-artists groups using a variety of creativity and personality tests, and found that dance students had more developed creative thinking, preferred movement over immobility in drawings, and produced more dynamic drawings than non-dancers. Other studies measured the influence of teaching methods on motor creativity, and the effect of dance on physical, cognitive, or creative factors (examples can be found in Morris, 2005).

Sociocultural aspects of the choreographic creative experience

In the 1990s, the field began to consider the sociocultural and political aspects of the choreographic creative experience, from pluralistic perspectives and with multicultural approaches (see, e. g., Albright, 2010; Franko, 2002; Press and Warburton, 2007). Sherry Shapiro (1998) explored the cultural, gender, and feminist aspects of creative processes in dance. Morris (2005) noted that new possibilities for creativity in contemporary dance were sparked by gender role reversal (for example, women lifting men) and same-gender partnering, and by the valuing of older, more mature dancers. He underlined the case of contemporary dance artists who involve non-dancers in local communities as collaborators, revealing a shift from virtuosity to a creativity *"claimed by all"*. He also argued that dance opens a window to the exploration of creativity by questioning traditional divisions among body, mind, and spirit. Jill Green (2002) discussed the combination of somatics with research on creativity and dance[12]. She argued that the use of somatics implies dealing with sociocultural influences on the body and seeing it as *"a tool for expressive movement and art making"* (Green, 2002). Doug Risner (1990; 2000) investigated dancers' experiences in rehearsals, providing insights about social dynamics in the choreographic creative process. He stressed the unique, personal nature of dancers' ways of learning, and urged choreographers to dive into this diversity when creating dances, and to question the assumptions and value systems embedded in rehearsals and in the creative process as a whole. Latulipe (2013),

11 See for example, the film documentary *Dancemaker*, directed by M. Diamond, Artistic License Films, 1998.

12 Thomas Hanna described somatics as the study of the *"soma"*, i. e. *"the* body *as perceived from within by first-person perception"* (Hanna, 1988). Hanna believed that proprioception provides unique data, and argued that although it is not better or more factual than the acquired through third-person perception, distinguishing them is fundamental for their use in the sciences.

in her defence of public funding for research in creativity and the arts, argued for promoting the intrinsic benefits of the arts and the qualitative benefits of enhancing creativity. She analysed the political challenges of scientists and technologists in interdisciplinary projects involving creativity and the arts, and suggested a careful examination of the relative privilege of science and technology, in order to avoid deepening the gap.

In summary, while the early methodology in general creativity research was, to a great extent, positivist and marked by large-scale quantitative studies, the take on creativity in the arts research and education fields emphasised ethnographic, participatory, and arts-informed qualitative methods, placing creativity within the scope of creative practice (Burnard, 2007). In their review of the literature, Press and Warburton (2007) signalled the scarcity of empirical research, and identified three possible topics of investigation to further develop the research on creativity in dance: 1) the role of interpersonal engagement in supporting the creative process (e. g., the weight of dance teachers' beliefs on the nature of creativity); 2) the dance languages and *"dialects"*, and their biological, environmental, creative, and experiential antecedents; 3) the use of technology in the physically distributed reality, including the tools and languages that define dance cognition.

Effects of notation and annotation on creativity

Over the last two decades, researchers examined the relationships between formal notation systems, personal annotations, and creativity. For example, Hutchinson Guest (2005) developed the *Language of Dance (LOD)* approach, based on *"actions"* and Laban-based notations, with the goal of advancing movement literacy and dance knowledge, as well as fostering creativity in composing movement sequences. Warburton (2000) used the *LOD* approach to examine the impact of notation on young dance students, finding a high correlation with thinking patterns that improved knowledge acquisition and creative expression. delaHunta et al. (2004) studied how choreographers use *"markings on a page"* as a visual language, as a source of innovation, and as tangible traces of their creative process. delaHunta (2015) raised the question of whether choreographic ideas and processes can reveal aspects of creativity or even the underlying structure of a dance. He described examples of score-generating systems from famous choreographers, and noted that they constitute *"objects of self-reflexive study"*, which could be examined by other researchers, for example, those investigating embodiment. Similarly, choreographer Jonathan Burrows (2010) proposed two approaches to the concept of a score: *"a representation of the piece itself"*, and *"a tool for information, image and inspiration"* that works as a source for the final product but whose shape my differ greatly from it. Alan Blackwell studied cognitive aspects of design and notation systems. He collected notebooks and scores from Wayne McGregor and several dancers from his company, and used methods from experimental psychology and design research to analyse McGregor's experience regarding the limitations of his own design tools (deLahunta and Zuniga Shaw, 2006).

Distributed creativity and embodied cognition

Another important part of this story is the cognitive approach applied to choreography, which uses theories in cognitive science to explore aspects of choreographic thought and creativity. Stevens et al. (2000) coined the term *choreographic cognition* to refer to the perceptual, cognitive, and emotional processes that mediate the creation and the performance of contemporary dance. They argued that creativity in contemporary choreographic cognition is increasingly marked by the collaboration between dancers and choreographers, and thus, any attempts to explain creativity in choreography must consider this dynamic. The authors identified cases of problem finding and solving during choreographic cognition. For example, choreographers and dancers must use and negotiate space and time in relation with the constraints imposed by the human body. As described by Stevens et al., *"time, space and motion are the media for choreographic cognition"*.

In a subsequent article, Stevens (2005b) suggested that choreographic cognition could be used to test psychological theories addressing creativity. With the goal of relating aspects of the choreographic process to existing theories of creativity, Stevens et al. (2003; 2005a) studied the creative process behind the piece *Red Rain*, by contemporary choreographer Anna Smith and a group of eight dancers. The authors analysed annotated video of the creative sessions, and the diary entries made by the choreographer and one of the dancers. They found that the creative process of *Red Rain* could be described as a cycle of generative and exploratory activities, and concluded that creativity in choreography composition resides in both the generation of movement material, and its sequencing, melding and linking. The authors argued that capturing the development of a choreographic piece, which is a complex case of artistic manifestation, can provide insights about creative thinking, for example, in terms of problem finding and solving, metaphorical thinking, synthesis of contradictory ideas, and multimodal imagery.

Kirsh and colleagues addressed dance from a creative cognition perspective, stressing distributed creativity and embodied cognition. Regarding distributed creativity[13], Kirsh et al. (2009) ran an ethnographic study of the creative process of choreographer Wayne McGregor and the dancers from his company, Random Dance. They found that McGregor used three methods for generating novel choreographic content — showing, making-on, and tasking— and suggested that these methods can be applied to other creative activities, especially those involving distributed creativity. They noted that *tasking* provides dancers with more resources when they need inspiration, and that imaginary structures can act as scaffolds to think with. In another article, Kirsh (2010) dealt with these structures in more depth, discussing ways in which external representations augment cognitive power by acting as scaffolds and vehicles for thought. He drew examples from choreography, showing how an annotated video by choreographer William Forsythe revealed the underlying structure of a movement, and created a *"shareable object of thought"* that served the choreographer and the dancers when creating or reflecting on a piece, and the audience when observing it.

Kirsh (2011a) argued that contemporary dance can teach us about embodied cognition[14], and other creative processes that leverage sensory systems. Moreover, he emphasised that dance is an interesting case study since the creative process generally takes several weeks and involves choreographers and dancers generating a great number of ideas, which are then selected and refined. As a result of deep ethnographic work with choreographer Wayne McGregor and Random Dance dancers, Kirsh asserted that the translation of ideas across sensory modalities in an embodied form enhances choreographers' and dancers' creativity, by making connections easier to discover and by leveraging the power of multiple representation systems. According to Kirsh, dancers use their bodies as a cognitive medium: Embodied cognition could be seen as a form of computation where the body is used to simulate a process, and by doing so, to understand the process. More recently, Kirsh (2013) analysed how embodied cognition, and the way it is used in the choreographic creative process, can inspire HCI researchers and practitioners working in novel interaction design. Similarly, Barnard and deLahunta posed dance and choreography as *platforms* to study embodiment: *"Dance (...) can be*

13 Seen as *"the mechanisms by which team members harness resources to interactively invent new concepts and elements, and then structure things into a coherent product"* (Kirsh, 2011a).

14 Understood as *"the mechanisms by which creative subjects think non-propositionally, using parts of their own sensory systems as simulation systems, and in the case of dancers, using their own (and other's) bodies as active tools for physical sketching"* (Kirsh, 2011a).

performed or experienced without a continual flow of explicit verbal thoughts. Yet in domains of making dance, notating it, or discussing it those abstract senses of meanings are translated into verbal thoughts or graphic notations. Thus, dance and choreography provide a unique platform for studying, using both quantitative and qualitative methods on how thought and abstract senses of the embodied self work"[15].

delaHunta et al. (2009) collaborated with choreographer Wayne McGregor in the project *Choreography and Cognition*, with the goal of exploring links between creativity, choreography, and cognitive science. Among other initiatives, the researchers proposed McGregor and the dancers in his company to parse videos of their dance into temporal units of movement, via a digital interface (deLahunta and Barnard, 2005). Then they built visualisations of the results in order to reveal abstract properties embedded in the perception of dance. They also developed techniques for augmenting the choreographic process. For example, they sampled short segments from the videos to use as a tool for fostering memory and creativity.

Cognition in choreography is not only distributed across choreographers' and dancers' brains and bodies, but also physical and digital artefacts, such as their notebooks and video of rehearsals (Sutton, 2005). As described by Sutton, in the process of transmitting, selecting, and transforming movement, *"particular movements and sequences could loop out into the world, jump across bodies, get tried out briefly and discarded or remoulded, and then be accessed again and again later through the enduring technological record"* (Sutton, 2005). With cognition physically distributed throughout digital tools and culture, technology offers opportunities for supporting creativity by acting not only as an *external memory* (Donald, 1991), but also as a partner or ally for thinking and acting (Suchman, 1987; Hutchins and Klausen, 1996; Hollan et al., 2000).

SUPPORTING CREATIVITY IN CHOREOGRAPHY

Enhancing creativity through pedagogy and critical evaluation

Besides the afore mentioned work about improving the choreographic creative process, some researchers explicitly explored the effects of teaching choreography composition on creativity. They focused on aspects such as movement exploration, improvisational skills, and teachers' approaches to creativity[16]. For example, Chappell and colleagues (2005; 2009) looked at pedagogical programmes that teach creativity through dance to young

15 Barnard and deLahunta. Presentation at *Underskin Symposium*, *La Biennale di Venezia* Dance sector, Venice, 9 June 2006.

16 A review can be found in Press and Warburton (2007).

students. Blom and Chaplin (1982) focused on the translation of felt experiences into external forms, stressing the role of improvisation when creating individual choreographic vocabularies. For them, aiding people to define a *"strong but flexible personal movement style"* was fundamental for the development of individually creative artists. Interestingly, they stated that *"choreography as a skill which can be taught and learned is the means and the method whereby creativity can be structured"*.

Watson et al. (2012) ran a longitudinal study with young dancers, teachers, and visiting choreographers in a contemporary dance training programme. The goal was to discover how creativity could be enhanced and facilitated in and through dance. Their results suggest that enhancing creativity at an individual level requires the development of personality capacities and traits (such as vulnerability, courage, self-confidence, and openness) with inspiration and motivation as the main driving forces of their evolution. They also found that the extent to which dancers were able to be creative depended on interpersonal and environmental factors, notably the relationships with the teachers and visiting choreographers. The authors advocated for collaborative, exploratory approaches and teaching styles that transmit dance skills while encouraging dancers to find and express their own voice. Interestingly, for the authors, *"it is vital that [creativity] is not positioned purely as a tool for choreography"*, as the reciprocal exchange between teachers and dancers benefits their creative development and personal growth — which constitutes a view of creativity as a humanising, transforming force.

Larry Lavender (2006) proposed mentoring as a technique for facilitating the creative process of beginner and advanced choreographers. He presented a descriptive model of the *"operational moments"* in choreography composition, and suggested how a mentor could help choreographers face the challenges that arise in the process. The four basic operations in the model are improvisation, development, evaluation, and assimilation, and can appear several times in the iterative process. As an example of mentoring, Lavender described a technique to help choreographers articulate their *"to-be-done ideas"* that consists of asking them to complete the following statements: *"'I am making a dance by...' (describe a process or method of working); 'I am making a dance in which...' (describe specific images for the work); and 'I am making a dance that...' (state desired outcomes the work will achieve)."* Lavender argued that this exercise helps choreographers refine their intentions and detect future challenges, sometimes leading to the transformation of an idea earlier in the process to avoid heavier reworking later.

Donna Davenport (2006) proposed an approach for building dance composition courses based on the following pedagogical principles: critical reflection, reason for dance making, exploration and experimentation, aesthetic agenda, thematic integrity, and expression and experience. She argued for giving creativity a key role in the design of dance composition courses, with an emphasis on the creative process and not only on the creative product. Davenport, as Blom and Chaplin, considered improvisation as a critical tool for movement generation and exploration, and a technique to *"think divergently"*, and to *"practice courageous, creative behavior"*.

Lavender (1996) defended the role of critical evaluation in dance creativity. He critiqued the *"idealist notion"* that assumes that art works exist fully formed in the creator's mind and represent predetermined meanings and content, from the beginning through the end of the creative process. Lavender argued that this notion prevents dance students from exploring movement, taking risks, and embracing change, and may make them feel that the choreographic process itself distorts the meanings that they try to convey through movement. This resonates with Maudet's (2017) critique of current design software tools, which assume that design follows a *hylomorphic model of creation* (Ingold, 2009) where the designer already has the idea in their mind of what they want to achieve.

Designing CSTs for choreography

Technology can support creativity during the choreographic process by facilitating generation of choreographic material, real-time interaction between dancers and technologies in performance, or reflection upon composed work[17].

Computer-assisted generation of choreographic material

As early as the 1960s, scientists started to explore the potential of computers to assist the generation of choreographic material. In 1967, Bell Labs' engineer Michael Noll developed a system to design ballet dancers' trajectories on stage, including basic limb movements[18]. The user could configure the motion patterns of stick figures representing dancers, via an electronic pencil (Fig. 4). The system produced static images that stayed on screen for the corresponding number of frames, while a camera photographed them to generate an animated sequence on film. Noll anticipated the possibility of combining *"order and randomness"* as well as the need to embed constraints: He envisioned a future where *"individ-*

17 See Fdili Alaoui et al. (2014), Carlson (2016) and Birringer (2002) for comprehensive reviews.

18 A video illustration can be found in: https://www.youtube.com/watch?v=phVN_HS5Fy8

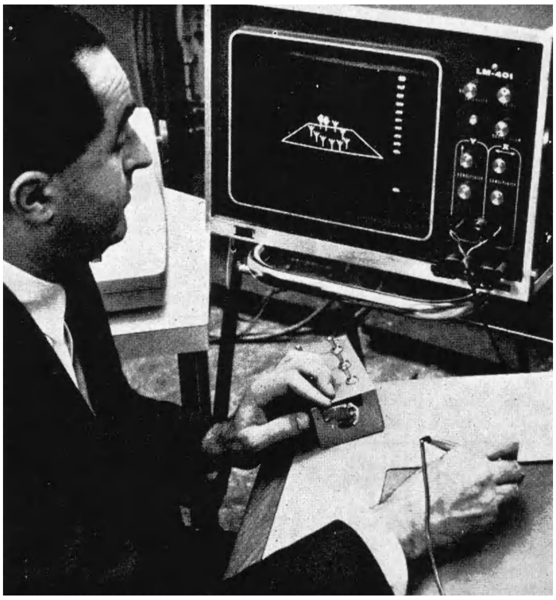

Figure 4: A user configures dancers' trajectories with a pencil in Noll's system. Source: Noll, 1967.

ual movement restrictions for each dancer could even be introduced into the process" (Noll, 1967). Noll was also one of the first to advocate for research on *"the process of human movement notation and choreography"*. Following Noll's vision, Carol Withrow (1970) developed an interactive system where the user drew curves with a pen on a tablet. The system related the curves to angular movements of the body joints and limbs shown in a display, in order to animate stick-figure representations of dancers.

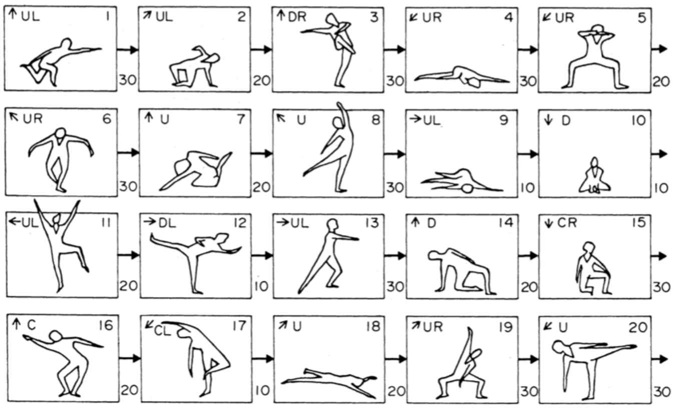

Figure 5: Output script in Lansdown's system. Source: Lansdown, 1978.

John Lansdown (1978), a computer graphics pioneer, produced an early reflection on computers and choreography. He analysed the approaches to computer art that existed back then, notably the probabilistic (incorporating randomness into creative decisions) and the deterministic (based on grammar-like rules). Lansdown argued that *"the appeal of computer art lies in the procedures used to produce it —the computer methods used are as interesting to the artist as the final outcome"* (Lansdown, 1978). He also described a program created by him that assisted the generation of dance sequences through a specific grammar and a vocabulary of movements, parts of the body, directions, levels, and timings. The computer provided only the key-frames of the dance — based on parameters chosen by the choreographer or the system — in the form of simplified human-body drawings, and the dancers had to compose the transitions (Fig. 5). In his experiments with dancers, Lansdown noted that the system challenged them to produce movements that deviated from their habitual vocabularies.

Meanwhile, choreographers also experimented with computer programs, mostly to break habitual movement choices. In 1964, choreographer Jeanne Beaman and scientist Paul Le Vasseur pioneered the exploration by using a program that randomised elements from three lists to generate sequences of instructions, in order to break dancers' movement habits (Reichardt, 1968). In 1969, choreographers Merce Cunningham and Twyla Tharp started playing with computerised chance methods (Parrish, 2007). For example, in the piece *History of Up and Down* (1971), Tharp used a computer program to generate and select from a list of suggested movements that encouraged unusual combinations (Parrish, 2007).

It took two decades after this early experimentation, and the emergence of personal computers, for researchers to start developing more flexible systems that choreographers could operate by themselves when generating new choreographic material. Among these systems, often based on visualisations of the human body, the most well-known is *LifeForms* (Calvert et al., 1993; Schiphorst et al., 1990; Schiphorst, 1993), later renamed as *DanceForms*. It relied on user selection of 3D skeletal postures to simulate dance movements that could be combined to create and edit new dance sequences (Fig. 6). The system was designed for choreographer Merce Cunningham, who used it in 1991 to choreograph the piece *Truckers*.

More recent tools include *iDanceForms*, which generates new movements using a camera still frame technique (Carlson et al., 2015a), and *Scuddle*, which uses genetic algorithms to trigger unfamiliar and thus novel movement choices, based on a minimalistic representation of the body (Carlson et al., 2011a). The system rates the body posture, the execution height, and movement qualities, in order to propose movement catalysts. Carlson et al. (2014) addressed the role of technology as a collaborator rather than as a tool, investigating how it can act as a creative agent in

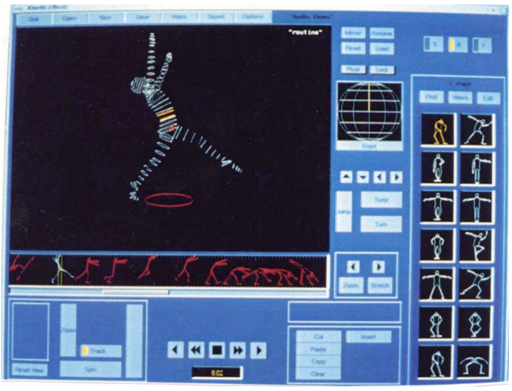

Figure 6: LifeForms' dance sequence editor window. Source: Schiphorst, 1993.

collaborative processes with users. They argued that the main reason for choreographers to interact with technology in the creative process is to perceive *"structural choices"* and augment their own kinaesthetic feedback. However, Carlson et al. noted that choreographers often react to the inherent limitations of technology by relying on their habitual movement choices and styles. The authors agreed with Candy (2007) that these limitations can instead be used as creative constraints. Moreover, they argued that for technology to behave as a collaborator, it must transform and elicit creative opportunities in such a way that the interaction sparks non-habitual responses in the choreographer, widening their creative range. Based on these premises, the authors proposed two concrete techniques for enhancing creativity by using digital systems as collaborators: modality shifts (prompting movement data in different representations) and abstraction (representing movement data with more or less ambiguity).

Figure 7: Loie Fuller's costume, ca. 1902. Source: Library of Congress, `https://www.loc.gov/item/96514367/`

Augmenting performance

As early as 1881, Loie Fuller created the *Serpentine Dance* in which coloured lights were projected on the voluminous folds of her silk costume while she danced (Fig. 7). She contributed with great innovations in stage lighting, cinematic techniques, and costume design (Current, 1997). In the 1930s, director Busby Berkeley introduced peculiar movement sequences in the world of cinema. His films featured dance sequences shot from above or unconventional angles that emphasised visual patterns, highlighted by extravagant costumes (Fig. 8).

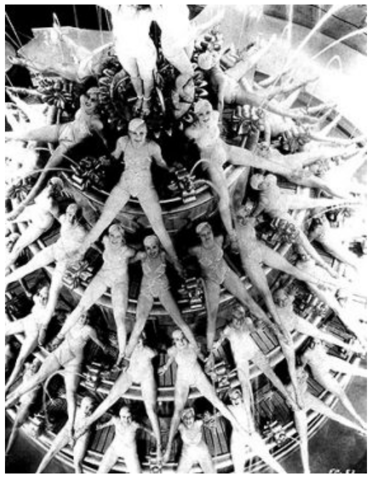

Figure 8: Screenshot from *Footlight Parade*, directed by Busby Berkeley (1933). Source: `https://en.wikipedia.org/w/index.php?curid=16624142`

In the 1960s, Merce Cunningham and John Cage worked on *Variations V* (Fig. 9), a piece where the dancers interrupting the path of photoelectric cells or getting closer to radio antennas triggered sounds that came out of six speakers distributed along the performance hall (Miller, 2001).

Figure 9: *"Variations V"*, by Cage and Cunningham, 1965. Source: John Cage, http://www.medienkunstnetz.de/works/variations-v/

By the 1990's, the group *Troika Ranch*, formed by composer/media artist Coniglio and choreographer Stoppiello, had extensively incorporated interactive multimedia in their live performances using tools designed and built by themselves (Kepner, 1997). For example, in 1989, Coniglio built *MidiDancer*, a wireless body costume with sensors that measured the flexion and extension of several body joints to manipulate multimedia in real-time. He also created *Isadora*[19], a tool for integrating video and interactive media to performance projects. Stoppiello choreographed using exclusively these tools over two decades[20]. The *Palindrome* dance company[21] has also worked on interactive performance pieces combining technology and art. Wechsler (1997a) described the *TouchLines* software, in which the user could draw lines over a video feed, and if any of the lines was *"touched"* by a dancer on stage, the system triggered changes in sound, lighting, or projections. Their system *Press Escape* tracked dancers by following their costume colour in order to control projections and music, based on the dancers' locations on stage and relative to each other.

In the 1990s, Merce Cunningham experimented with motion capture and virtual skeletons in his piece *Biped* (Abouaf, 1999), and choreographer and programmer Richard Lord created a completely *"digital dance"* only accessible online, which would get assembled according to the user's internet speed and their interaction with dance video clips on the website (Birringer, 2002). The dance company *half/angel* designed and programmed a chore-

19 Website: https://troikatronix.com/. Accessed on August 12, 2018.
20 Source: http://dawnstoppiello.com/mfa-portfolio-2-present/. Accessed on August 12, 2018.
21 Website: http://www.palindrome.de/.

ographic project that used motion sensing and MIDI software, where the system collaborated with dancers to augment them by combining movement improvisation, poetry, and sound (Birringer, 2002).

More recently, choreographer Pablo Ventura reflected on how the use of algorithmic concepts transformed his choreographic practice (Ventura and Bisig, 2016). He has produced computer-aided choreographies for the last two decades. For example, he used the *Choreography Machine* software to delegate creative decisions in order to break from habitual ways of composing, reaching the point of letting the system completely automate the generation of choreographic material. Ventura's use of *LifeForms* is an interesting example of reciprocal co-adaptation[22]: As he learnt to use the system and became familiar with its constraints, he appropriated it for his own needs (breaking his own habits and implementing his own algorithmic principles). In turn, the system shaped his choreographic vision, and made dancers incorporate the algorithmically specified movements into their repertoire.

Figure 10: Dancer in the *Double Skin/Double Mind* installation. Source: Thomas Lenden, `http://projects.beyondtext.ac.uk/choreographicobjects/uploads/grecofour.jpg`

Fdili Alaoui et al. (2013), together with the dance company Emio Greco|PC, created an interactive installation that incorporated visualisations of movement qualities developed by the company during their *Double Skin/Double Mind* workshop (Fig 10). The system recognises dancers' movement qualities through gesture analysis and responds to them with corresponding behaviours of interactive abstract visuals based on physical models. Jacob and Magerko (2015) explored human-computer co-creativity in dance, by combining a human performer and a virtual agent who improvise movements in real-time. Hattwick et al.'s (2014) family of digital musical instruments are worn as prosthetic extensions to dancers' bodies, influencing both their movements and the resulting music. Other researchers contributed with interactive sets including background visualisations, lighting, and sound (e. g., Meador et al., 2004).

These technologies for generation and real-time interaction could serve as a stimulus during the creation phase or for the final performance. They offer choreographers and dancers with new creative possibilities, but each was built to support a particular choreographic approach or idiosyncratic vocabulary.

22 An extension of co-adaptation (Mackay, 1990) that also considers the system adapting to the user (learning from them) and adapting the user (shaping their behaviour).

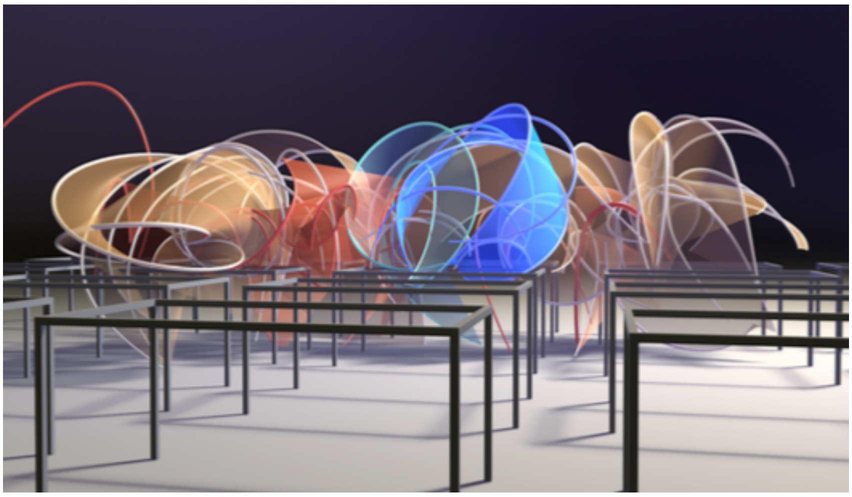

Figure 11: 3D alignment in *Synchronous Objects*. Source: https://synchronousobjects.osu.edu/media/downloads/Obj21_3DAlignmentAnim.jpg

Sparking reflection on choreographic material

Some projects explore interesting visualisation techniques to spark reflection on choreographers' current and past creations and practices. For example, the *Entity* project (deLahunta and Shaw, 2008), with the participation of Wayne McGregor, involves the design of adaptive software agents to solve choreographic problems, augment creativity, and establish principles of choreographic thinking. Other projects, such as *Synchronous Objects*, enable reflection by revealing choreographic structures and patterns through the visualisation of movement data (Palazzi and Shaw, 2009), as shown in Fig. 11. *ActionPlot* (Carlson et al., 2011b) is a prototype that enables structural analysis of contemporary dance pieces. It plots information provided by expert observers, such as the number of performers, their attention and intention, and characteristics of the performed movements, such as effort and tempo. I am inspired by these examples, although they were not designed for supporting the compositional process from the beginning.

From a pedagogical perspective, Kirk and Pitches (2013) investigated how teachers in choreography and other artistic disciplines can use digital technologies to facilitate students' reflection on their creative practices. They proposed a model of *"digital reflection"* in which technologies can be categorised according to how well they support reflection during a creative process. In their model, technologies can serve to capture the creative process (by filming, photographing, taking notes), to document it (by archiving the captured data), or to reflect about it (by enabling users to *"look/listen again"* digital artefacts and explain them in expressive ways).

From the more general perspective of movement representation, Alemi et al. (2014) created *Mova*. Mova is a prototype for visualising and analysing movement qualities and their relationships. The authors envisioned scenarios for several domains that use movement data, including sports and choreography. For example, a choreographer could use the extracted movement features (e. g., speed, acceleration, jerk) to assess dancers' performances and compare them.

Evaluating CSTs for choreography

In the existing literature, the evaluation of CSTs for choreography is typically performed by the designers of the tools, mostly through qualitative studies. One exception is Eckert et al.'s (2012) analysis of design process sketches. The authors focus on their properties, e. g., degree of formality, and discuss their role in idea generation, reasoning, and communication. As an example, they describe the *Choreographic Language Agent* (CLA) (Church and Blackwell, 2011; Church et al., 2012), designed as a visual end-user programming language for dancers to animate points and lines in three dimensions. The designers originally intended the system to show some level of agency and serve as a generative tool. However, dancers used it to define structures that did not represent bodies or body motion, but problems to be solved by translating them creatively into dance. According to Eckert et al., the CLA was a valuable creative resource that acted as a digital notebook and sketching tool, rather than as an intelligent agent. Interestingly, creativity was not embedded in the system, but in the interpretation of the sketches (Eckert et al., 2012).

3.5 CREATIVITY AND CONSTRAINTS

Every creative process develops under a variety of constraints stemming from the context and the creative agents. An architect building a museum might be constrained by, for example, the weight, shape, and cost of materials. A music composer creating a piece for piano and violin might break stylistic principles but is ultimately constrained by personal skills and by the acoustic properties of the musical instruments.

Many communities of practice use specific terms for the most relevant constraints in their domain. While engineers and software developers typically work with "*requirements*", film-makers, poets, and other artists refer to "*genre conventions*", "*rules*", or "*guidelines*", among other terms (Onarheim and Biskjaer, 2013). Because practitioners tend to load these words with personal meaning, Onarheim and Biskjaer advocate for the term "*creative con-*

straint" in order to facilitate interdisciplinary approaches to the study of creative processes. They define creative constraints independently of the domain, as *"all explicit or tacit factors governing what the creative agent/s must, should, can, and cannot do; and what the creative output must, should, can, and cannot be"*. I subscribe to this definition and I use the term constraint and creative constraint interchangeably.

THE DUAL ROLE OF CONSTRAINTS IN CREATIVITY

The role of constraints in creativity has attracted the attention of creativity researchers since the beginning of the field. Guilford (1950) highlighted the link between creativity and *"restraint"*. Since then, most of the theoretical and empirical contributions produced were domain-dependent, focused on a specific type of constraint imposed on the agent externally or inherent to the materials, and often viewed constraints as obstacles or demands[23]. Overarching approaches combining theoretical and empirical accounts or involving comparisons across domains are scarce (Onarheim and Biskjaer, 2013).

The relationship between creativity and constraints is crucial: Several authors have argued that what is not constrained cannot be creative (Boden, 2004; Horowitz, 1999; Johnson-Laird, 1988; Stokes, 2005). By definition, creative constraints affect creative agency, but not necessarily in a negative way. They play a dual role, both *limiting* and *enabling* creativity (Biskjaer et al., 2011; Boden, 2010; Elster, 2000; Isaak and Just, 1995; Joyce, 2009; McDonnell, 2011; Negus and Pickering, 2004; Onarheim and Wiltschnig, 2010; Reitman, 1964; Stokes, 2008). Margaret Boden (2004) described constraints as a means of mapping *"a territory of structural possibilities which can be explored and perhaps transformed to give another one"*. For Boden, *"far from being the antithesis of creativity, constraints on thinking are what makes it possible"*. Along the same lines, Linda Candy (2007) stated that *"creativity may be seen as a process of exercising free choice in the context of a range of existing constraints"*. For her, constraints help the creative agent work in a *"more manageable creative space"*. Similarly, Csikszentmihalyi (1996) suggested that freedom increases *flow*, but up to a threshold.

Onarheim (2012) showed that creative agents' perception of the limiting aspects of constraints is personal, context-dependent, and dynamic. Moreover, his studies of film-makers and engineering designers revealed that the same constraint was seen as limiting or as enabling by the same creative agent at different times.

23 Reviews can be found in Biskjaer and Halskov (2014); Onarheim and Biskjaer (2013).

HANDLING CONSTRAINTS

Constraints proliferate, as each new decision leads to new constraints (Reitman, 1964). For this reason, several authors highlighted the importance of managing trade-offs between conflicting constraints, as well as breaking the rules (Chevalier and Ivory, 2003; Csikszentmihalyi, 1994; Li, 1997; Stacey and Eckert, 2010). For Onarheim (2012), constraints are *"dynamic entities that can be manipulated to potentially produce a better situation for creativity"*. He stated that the usefulness of a creative product depends on the successful handling of relevant constraints. He also argued that knowing the constraints behind a creative process might impact the perceived creativity of the resulting product.

Stacey and Eckert (2010) proposed a continuum of problems going from *over-constrained* to *under-constrained*. Over-constrained problems, such as those in engineering design, involve detailed design briefs and expected outcomes. In under-constrained problems, such as those in artistic creation, the creative agent must handle self-imposed constraints to navigate *"the action space"*. The authors studied practitioners from three example domains in this continuum: engineering design, software development, and knitwear design. They found different patterns of constraints and strategies for constraint handling according to the type of problem. For example, engineering design emphasised solving contradictory constraints. Software development involved creatively finding the relevant constraints by imagining how the system would be used. In knitwear design, the focus was in constructing suitable constraints to frame the problem in a way that made it solvable.

For Stacey and Eckert, handling constraints involves four activities: *finding* the constraints in the problem; *constructing* new constraints by looking beyond the problem; *translating* constraints and exploring their implications; *resolving* contradicting constraints. When carrying out these activities, designers must distinguish between *strong* constraints (which must be met) and *weak constraints* (which can be relaxed).

Similarly, Coughlan and Johnson (2008) identified *static* and *malleable* constraints. According to them, malleable constraints are manipulated in *"cycles of constraint development"*, where creative agents analyse how constraints fit with each other, what would be the effects of introducing new ones, and implement the desired changes in the *"constraint structure"*.

MODELS AND TYPOLOGIES OF CONSTRAINTS

Sternberg and Kaufman (2010) published a comprehensive review of constraints that act on creativity. These constraints can relate to the *person*, the *process*, and the *product*. For example, the *person*'s motivation and personality are indeed constraints, but they can help the person overcome, to some extent, possible cognitive constraints. Components of the creative *process* place constraints on creativity, as shown by Stokes (2005). For example, some tasks are more likely to require creativity than others. A creative *product*'s contribution is constrained by society, and radical innovations are often discouraged when they defy the *status quo*. The authors also discuss *contextual* and *internal* constraints. Contextual constraints can be *random* or *systemic*. For example, social organisations, and more generally society and culture, impose systemic constraints upon the individual by encouraging or limiting creative behaviour. *Internal* constraints on creativity come from the individual, who sometimes is not aware of them. These constraints involve the person's skills, attitudes, and motivation. Relevant constraints within this group are: the risk-reward ratio (which depends on both internal and contextual constraints); the willingness to reframe problems, to criticise one's own creative work and to overcome obstacles; and the tendency to become stuck on a point of view due to consolidated expertise.

Some authors proposed models and typologies of constraints in the context of problem solving. One of the first contributions was Reitman's (1964), who posed that ill-structured problems are based on *"open constraints"*, i. e. constraints with parameters left unspecified. The problem solver may adjust those parameters to take a new direction on the problem.

Patricia D. Stokes (2007; 2008) proposed a rational problem-solving model for creativity. She borrowed Reitman's (1966) description of *"paired constraints"*, where one limits the search among existing solutions and the other guides the search to novel and often opposite solutions. She combined this concept with Simon's (1973) assertion about creative solutions emerging from incompletely specified or ill-structured problem spaces. In her model, paired constraints render problem spaces ill-structured, increasing variability and facilitating the production of creative solutions.

Stokes (2008) distinguished between four types of constraints: *goal* (stylistic conventions), *source* (elements to recombine), *task* (materials and how they get used), and *subject* (content or motif). According to her, the creative agent strategically selects the source, the task, and the subject to achieve the goal. She claimed that *"influential"* creativity *"depends on an expert selecting paired subject* *and task constraints to restructure an existing problem space"*. Stokes (2007) argued that novices work with constraints chosen by their teachers, and that becoming an expert implies mastering domain constraints. Moreover, Stokes and Fisher (2005) posed that *"artistic freedom exists only in the choosing of one's own constraints"*.

Although Stokes favoured an intended cause-effect relationship between selecting paired constraints and achieving breakthroughs, more empirical evidence is needed (Biskjaer and Halskov, 2014). In addition, her model restricts creative freedom to experts who can and are willing to work with paired constraints. It leaves out serendipitous exploration of creative solutions, as well as novices' learning processes.

Jin Li (1997) explored the link between creativity and constraints from a knowledge domain perspective. Interestingly, she pointed out the lack of a consensual definition of *knowledge domain*, but still advocated for probing into its interaction with the person and the field (in Csikszentmihalyi's terms). According to Li, each knowledge domain has associated structures that develop within cultural contexts over time. These structures are sources of domain-dependent, dynamic constraints that shape the process of creativity. To explore this relationship, Li proposed to analyse domains as *horizontal* or *vertical*, according to the constraints they impose on creativity and their degree of *"openness to novelty"*. Horizontal domains enable creativity to flourish *"in an indefinite number of dimensions"*, producing *"divergent developments"*. Creative endeavours in this type of domain sometimes revolutionise it, breaking from the traditionally established practice. Vertical domains, by contrast, are characterised by existentially fundamental elements forming a highly stable conventional core. They enable creativity to occur only within a restricted set of dimensions that do not modify the domain's identity. Li posed Western painting as an example of horizontal domain and Chinese painting as a vertical one. Li's division of domains between horizontal and vertical is not absolute, and domains exist on a spectrum. Moreover, within a domain, some dimensions might be vertical and some horizontal. For example, classic ballet could be seen as vertical, while modern and contemporary dance as horizontal, but richer differences could be detected within each of these domains depending on particular cultural practices. Li argued for paying special attention to the extremes of the continuum, as they differ in their structural constraints and their effects on creativity. She offered five structural parameters to analyse vertical and horizontal domains: *aim, methods, symbol systems and use, rules, and standards*.

Similar to Li, Linda Candy (2007) identified two types of constraints in artistic practice: constraints chosen by the artist, and constraints inherent to the genre and the medium. The genre is the *"basic creative conceptual space in which rules and conventions impose a set of boundary constraints within which the artist works"*. The decisions made within this space determine the individual style of the artist, together with their use of medium constraints.

For the specific case of architectural design, Lawson's (2006) typology of creativity constraints organises them in a cube. The model classifies constraints according to their *domain* (internal or external), their *sources* (users, clients, designers, legislators), and their *function* (radical, practical, formal, symbolic).

Other authors approached constraints from a cross-disciplinary perspective. In his philosophical essays, Jon Elster (2000) divided constraints into *intrinsic* (inherent to the materials), *imposed* (by external agents), and *self-imposed*. Although Elster did not focus on creative processes, the concept of self-imposed constraints is highly relevant for this thesis.

In the last decade, some researchers picked up the topic of self-imposed constraints. For example, Biskjaer et al. (2010) found that self-limitation expands interaction designers' resources. Onarheim and Biskjaer (2013) introduced *"decisive constraints"*, a type of self-imposed constraint that produces an abrupt change in the creative process, leading to a highly creative output.

So far, the most comprehensive effort to understand and classify creative constraints and their typologies is perhaps Onarheim's (2012) doctoral dissertation. Based on an extensive review of the literature and his own observations of creative practitioners in several domains, Onarheim identified a variety of constraints, spanning from technical and practical to social and cognitive. He classified constraints into seven categories (individual, social, process, technical, source, domain, purpose) and synthesised a conceptualisation of constraints involving seven dimensions (articulation, abstraction, complexity, flexibility, importance, origin, timing), each corresponding to one or more continua of constraint types.

CONSTRAINTS AND TECHNOLOGY

Linda Candy (2007) reflected on the role of constraints in the domain of digital arts, and the impact of technology on creativity. Constraints *"might be thought of as personal* 'rules' *that capture the significant elements that the artist chooses to focus upon"*, for example, *"colour, relationships between objects in the scene, sequences (in time-based work) and movement and location (in interactive work)"*. The use of technology in this context comes with additional constraints related to the nature of computers and the relative youth of the medium. This has given place to a range of approaches in the integration of technology and art, from *"digitalising"* existing forms, to radically changing them. For some artists, Candy said, the digital tool with which they work cannot be separated from the digital medium.

Candy noted that to use technology in their work, artists need to make explicit their implicit assumptions, which can be both challenging and rewarding. Moreover, to work with constraints digitally, these must be specified in a way that computers can handle. Candy argued that the process of specifying personal artistic constraints digitally is *"an integral part of the creative process"*. As this often requires the artist to program, it might imply collaborating with technologists. I agree with Candy in that the power and flexibility of programming languages give more control to the artist over constraints than software applications. Still, I believe that this is partly caused by software applications not considering constraints as an essential part of the creative process, thus not giving users the chance of specifying and interacting with their personal constraints without having to program.

Candy also reflected on constraints and structure: Specifying constraints in a computer program can help the artist understand their implications and the *"underlying structure"* of a digital art piece, based on the program's ability to *"represent and 'execute'"* this structure. Making constraints explicit is for Candy *"a kind of boundary definition of a personal creative space"*. The integration of digital technology into the creative process produces then a *"highly constrained creative space"* but this can lead to new artistic paths.

Similar to Candy, Coughlan and Johnson (2008) argued that technology for creative tasks both constrains the creative process and offers new creative possibilities through end user development. They built *Music Builder*, a prototype that allows users to design musical instruments collaboratively. Through user studies, the authors explored the role of constraints in mediating creative collaboration. As a result, they suggested that software environments for creative tasks should provide users with scaffolding to quickly build and explore structures, combined with the visualisation of constraints during constraint development in order to facilitate collaboration. They concluded that these environments *"should fluidly integrate the representation of ideas and of constraints and allow users to explore the interdependence of the two"*. Although I have the same goal, I do not approach it from an end user development perspective. Instead, I argue that users should be able to create their own representations of creative ideas and constraints, and that this should be achievable without programming.

3.5.1 *Constraints in design*

Most design-oriented disciplines recognise constraints as a fundamental part of the creative process (Gross, 1986). Onarheim (2012) argued for considering the *"crucial relationship between constraints and creativity"* for understanding and supporting creativity in design. With a more radical view, Chandrasekaran (1990) stated that *"all design can be thought of as constraint satisfaction, and one might be tempted to propose global constraint satisfaction as a universal solution for design"*. Similarly, Simon (1996) stated that *"design solutions are sequences of actions that lead to possible worlds satisfying specified constraints"*. Logan and Smithers (1993) also put constraints at the core of design. They reflected on how a design decision seemingly associated with a simple criterion often has an impact over other aspects of the solution, revealing previously hidden relationships. The authors defined the structure of a design problem as the interactions between these relationships. They argued that the essence of a design problem is given by the pattern of constraints that define the problem space's structure, and that discovering their relationships is the base of the design activity.

Peter Dalsgaard (2017) discussed constraints in the frame of *instruments of inquiry*, described in Section 3.3. For example, in the *perception* category, instruments play a dual role: they both extend a designers' capabilities and shape their perception, according to hidden and exposed constraints.

An important empirical contribution about the link between constraints and creativity was provided by Caneel Joyce (2009). She studied the role of task instructions in product design and found that creativity relates to different degrees of constraint in an inverted U-shaped curve. She showed that too much constraint decreases the motivation to create, and that too few generates the paradox of choice.

Constraints can play a diversity of roles in design, helping designers generate and evaluate the functionality, structure, and behaviour of creative products (Onarheim and Wiltschnig, 2010). For example, Onarheim (2012) identified the existence of *crucial* constraints, which become the focus of the creative effort, and *late* constraints, which can require a re-examination of the current design solutions and potentially spark creativity. Designers may also introduce *overarching constraints*, such as *"the product needs to be sporty"*, which are abstract and not measurable, but later give rise to more concrete constraints. However, he also showed that constraints without clear explanations or owners can be a barrier for creativity, as well as *tacit constraints* stemming from designers' beliefs. Onarheim described the types and roles of constraints in design through four continua: *hardness* (how hard it is to measure), *importance*, *flexibility* (how challenging it is to change), and *level of formalisation*.

HANDLING CONSTRAINTS IN DESIGN

Biskjaer and Halskov (2014) explored the concept of *"decisive constraints"* in interaction design. These are non-trivial and often counter-intuitive self-imposed constraints that imply *"radical decision-making"* and reduce considerably the solution space. Decisive constraints are employed intentionally by the creative agent to accelerate the creative process, acting as catalysts for *"creative turning points"* — or leading to a dead-end.

On the other hand, designers often engage in playful *"bending"* or *"testing"* of constraints to promote unexpected solutions (Onarheim, 2012). Onarheim found that designers employ four strategies for constraint handling: *blackboxing* (treating a constraint as unchangeable), *removal* (removing a conflicting constraint), *revision* (re-examining an existing constraint) and *introduction* (adding a constraint when becoming stuck).

For Onarheim, constraint handling consists of balancing a set of constraints, searching for the *sweet spot* of creativity, i. e. the desired level of *constrainedness*. The concept of constrainedness articulates the level of experienced creativity constraints at a certain point in the creative process (Biskjaer et al., 2011; Onarheim and Biskjaer, 2013). Its manipulation implies balancing the dual role of constraints as limiting and enabling. Recently, Onarheim and Biskjaer (2017) went deeper into the concept of sweet spot, which refers to the situation in which a creative agent experiences *"the 'right' level of constrainedness"* leading to *"optimum creative performance"*. Based on their previous studies in art and engineering design, the authors suggested that at the beginning of the creative process the agent is not within the sweet spot, and thus needs to use tools to manipulate the level of constrainedness. They also believe that creativity is closely related to situations in which *"articulated or unspoken rules are meaningfully broken, while at the same time the domain or ambient culture accepts the violation of the old and the establishment of new rules"*.

Biskjaer and Dalsgaard (2012) proposed a pragmatist approach to constraints in design creativity. Their approach implies analysing *creativity* as a *"distributed phenomenon"* between people and technological resources. It also implies viewing *design* as an *"inherently technological mode of inquiry"*, as constraints form a *"technology"* that guides the design process and helps reframing the problem and the solution. In addition, analogue or digital tools and resources give rise to constraints that designers often take for granted, internalising them through repeated use. Finally, it implies understanding *design creativity* as an *"emergent, situated, and reciprocal process"* that encompasses both action and reflection and involves reciprocity between the person and the environment. My approach aligns with their view, as they highlight the designer's ability to engage with the design situation through direct experience and the mastering of constraint manipulation. While they advocate for this pragmatist, reflective approach as a means to get new insights on creativity, I am concerned instead with the building of interactive tools to support the creative manipulation of constraints.

3.5.2 *Constraints in choreography*

The choreographic creative process unfolds under a variety of constraints coming from the people involved and the context in which the dance project exists. The production of a dance piece typically gathers a variety of stakeholders that interact at different levels, going from choreographers, dancers and the audience in small projects, to also sound and light technicians, costume designers, stage designers, funding committees, and even technologists and dance notators in bigger projects. The choreographers' background, skills, and style of dance making, as well as their motivation and inspiration, are the source of important creative constraints. These constraints are combined with the ones stemming from dancers' background, skills, and personal signature to create movement and perform it, together with their motivation, expectations, and the particularities of their bodies. Ultimately, as the main medium for contemporary dance is movement, the human body imposes limitations on the types of movement and transitions that a human dancer can perform. The collaboration between choreographers and dancers, and the dancers' interpretations of instructions and scores also constrains the creative process and product.

Another fundamental source of creative constraints is the dance genre. Contemporary dance imposes a set of values and conventions that a choreographer might decide to accept, to choose from, to bend, or to challenge completely. As noted by Candy (2007), the use of technology in the creative process brings additional constraints relative to the digital medium. Other constraints are related to budget, characteristics and availability of the studio and the performance venue, safety and health laws, regulations that determine the number of hours that dancers can work per week, etc. Moreover, some countries with censorship policies might restrict the subjects that can be depicted through dance, or even the costumes and interactions between dancers.

On top of all these constraints, many contemporary choreographers introduce self-imposed constraints to guide the creative process. These constraints articulate their creative ideas, principles, or guidelines, shaping a creative design space that they explore in idiosyncratic ways. Several famous choreographers have explicitly defined their own methods of composing dance through the manipulation of creative constraints. Stokes (2008) described how choreographer Merce Cunningham used chanced methods to avoid getting stuck in successful solutions. For example, he threw two coins together to decide the temporal order of a set of movements. Stokes argued that the use of the coins avoided repetition while promoting variability, and that the existence of the set of movements avoided chaos while promoting continuity.

Choreographer Anne Teresa de Keersmaeker develops her main intention for a piece by *"producing constraints that will drive the creation toward overcoming an initial difficulty"* (Cvejic, 2017). For example, in *Drumming*, the difficulty resided in creating a dance to a piece of contemporary music by composer Steve Reich that maintained a relentless rhythm for over one hour. In her early projects, she heavily relied on spatial constraints to compose the space, designing complex geometrical patterns to decide the order and the place of movements on stage (Fig. 12). These patterns were based on circles, squares, diagonal lines, and grids that evolved over time, and were strategically underlined during performance through lighting (De Keersmaeker and Cvejic, 2012). Her later works used spatial constraints in simpler and more minimalistic patterns, with a progression from the *"the simplicity of walking to the fullest complexity of dancing"*[24]. Cvejic (2017) described how De Keersmaeker composes the time in her dance pieces through parameters that constrain the dancers and their movements: *"Analogous to the spatial development is the* timeline plan *of the whole, which regulates the distribution of levels of intensity in the experience of the duration of choreography: a composition of a curve of attention, indicating peaks and anticlimaxes, moments of contrast or of recapitulation"*. De Keersmaeker also uses self-imposed constraints deciding whether to construct the choreography based on one *"formal principle"* or *"divergent sections"* that follow different criteria. *Drumming* is an example of former, as the whole piece is based on a single dance phrase that gets repeated with variations in space and time, over a golden spiral spatial pattern. In addition, De Keersmaeker masters the counterpoint technique, a strong creative constraint that relates dance and music: *"It details the effect of the distribution of movements among dancers upon the*

24 Source: Official website of *Rosas*, Anne Teresa de Keersmaeker's dance company, https://www.rosas.be/en/8-anne-teresa-de-keersmaeker. Accessed on September 21, 2018

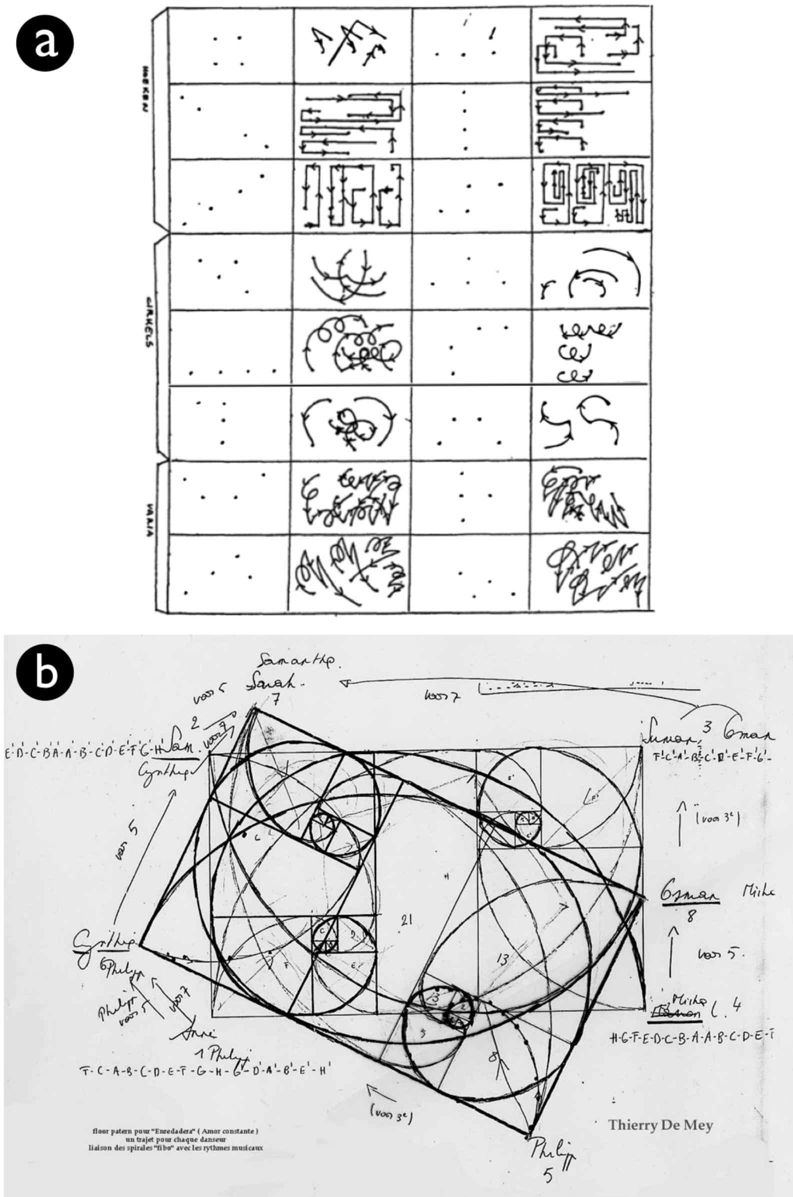

Figure 12: Spatial floor patterns in De Keersmaeker's pieces: (a) *Rosas Danst Rosas*, source: Cvejic (2017); (b) *Amor constante más allá de la muerte*, diagram by Thierry De Mey, source: http://olga0.oralsite.be/oralsite/pages/Thierry_De_Mey/

'texture' of the dance, combining the musical technique of superimposing divergent lines (...) with the geometrical patterns appearing from many bodies dancing together as if to form a fabric" (Cvejic, 2017).

Choreographer Trisha Brown developed several *"choreographic systems"* that she used as score-making tools (deLahunta, 2015). In 1978, Mona Sulzman, who was at the time a dancer in Brown's company, described one of such systems, called *Locus* (Sulzman, 1978). Locus involves an imaginary cube of space, slightly larger than a standing person with arms and legs outstretched. The cube is represented on a diagram with 27 numbered points (Fig. 13). Each point corresponds to a letter in the alphabet: 1 is A, 2 is B, and so on. Brown wrote a short autobiographical fragment, and mapped each letter to the corresponding point on the cube (Fig. 14). Then she created four dance sections that *"move through, touch, look at, jump over, or do something about each point, either one at a time or clustered"* (Trisha Brown, as cited by Sulzman, 1978). The imaginary cube is repeated to form a grid of 5×4 rows. During performance, dancers must choose the dance section, the direction they face, and their own placing, being free to move from one cube to another. In this way, they have to problem-solve while moving under the constraints posed by the choreographic system. deLahunta (2015) argued that this type of score generation tool and its instructions are co-dependent with the *"evolution of a unique way of dancing"*. The artefacts representing Brown's ideas exemplify co-adaptation and substrates: they organise constraints into a coherent system that dancers adapted to, but also adapted — since they appropriated the mapping by reinterpreting or redefining actions to perform at each point.

Unlike the case of design disciplines, research focusing explicitly on constraints are not as common in choreography, and works relating constraints and technology are even more scarce. A historical example is Lansdown's (1978) article *The computer and choreography*, in which he explained that works of *"computer art"* emerge from the computer manipulating representations of pictures, texts, or sounds. Although Lansdown did not call them constraints, he did talk about *"the rules that determine the legality of a particular manipulation"*. These rules are syntactical, with no semantic meaning, and act upon a vocabulary of elements *"akin to words of a natural language"*. However, in Lansdown's vision, the role of the user would be limited to providing the computer with these rules in order to generate dance.

Interestingly, Schiphorst et al. (1990) described the ill-structured nature of dance making as a specific type of design problem: *"In creating a dance we often do not have a fixed problem space, a clearly defined goal state, or a discrete set of defined transformations we would like to employ in order to reach our goal"*. They also re-

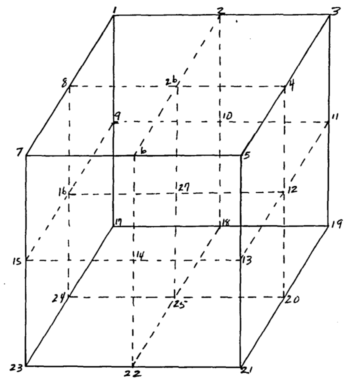

Figure 13: Trisha Brown's *Locus* choreographic system: A cube of 3D space with 27 points. Source: Sulzman (1978).

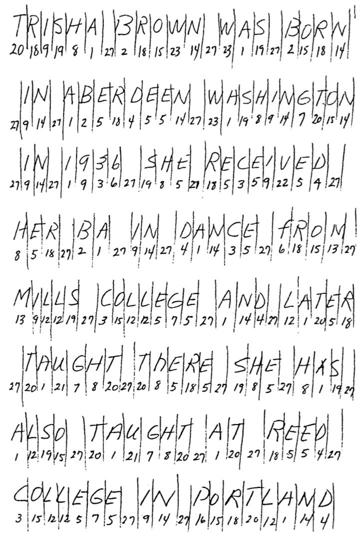

Figure 14: Trisha Brown's *Locus* choreographic system: Fragment used to generate the score. Source: Sulzman (1978).

ferred to the manipulation of the problem and the constraints when trying to produce a creative solution: *"A creative solution results in a shock of recognition, and is often the result of coming to the boundary or limits of the solution space. It is now either the limits or constraints, or the problem itself that must be redefined"*. In the same article, the authors described the interface of the *COMPOSE* system (which later became *LifeForms*) as a *"constraint-based reasoning system"* that would help choreographers integrate and manage diverse constraints related to human movement and its temporal sequencing. A more recent example is Kristin Carlson's (2016) work on constraints and defamiliarisation techniques for choreographers to break from their movement habits.

3.6 CURRENT STATUS OF CREATIVITY RESEARCH IN HCI

Recently, Frich et al. (2018b) published a survey on the last twenty years of creativity research in HCI. They found that contributions generally lacked a definition of creativity, focused on collaborative creativity, involved in-vitro studies (instructed tasks in controlled environments), and often tested tools designed by the researchers rather than the ones used by participants. Similarly to Hewett et al. (2005), the authors argued for in-vivo studies of existing tools. They also encouraged inter-disciplinary approaches that facilitate comparisons across fields.

My research approach (described in Section 1.2) takes a step towards addressing the gaps identified by Frich et al. In particular, I use HCI methods to study current creative practice, to design novel tools for supporting it, and to observe these tools in use, combining in-vitro and in-vivo studies. I base my theoretical contributions on HCI theories and models (Chapter 2), but I also recognise the plurality of disciplines in play, by drawing from dance research, and by incorporating the first-person perspective provided by study participants and by one of my advisors who is also a choreographer. Rather than focusing on typologies of constraints or methods to handle them, I seek to understand practitioners' practices, in order to design interactive tools that support exploration and documentation of both content and constraints.

Part I

SPATIAL CONSTRAINTS IN GRAPHIC DESIGN

This part explores the definition and manipulation of alignment and distribution constraints as concrete examples of spatial constraints that designers make use of when designing graphical layouts. I first study the current practices of designers and regular users of graphical editing tools (Chapter 4), and then I propose and evaluate StickyLines, *a tool that addresses users' needs in this context (Chapter 5). This work has been done in collaboration with Nolwenn Maudet, Michel Beaudouin-Lafon and Wendy Mackay.*

When designing a graphical layout for a digital document, designers need to organise objects in 2D space, such as text, images, or shapes. Aligning and distributing graphical objects are among the most common strategies to achieve aesthetically pleasant results in this context. Current commercial systems typically feature a set of 12 commands to align or distribute a set of objects, either horizontally or vertically (Fig. 15). For example, a horizontal *align-centre* command uses the geometric centre of each object to move the selected objects vertically. Similarly, a vertical *distribute* command either positions the objects evenly along the vertical axis, using their centres as reference points, or spaces them evenly, using their tops and bottoms to distribute the available space between objects.

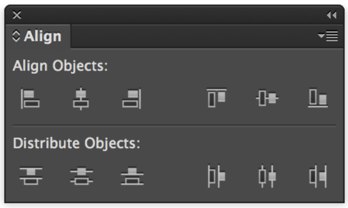

Figure 15: Alignment and distribution commands in Adobe Illustrator.

From a conceptual perspective, we can see aligning and distributing objects as methods to establish spatial relationships between them. These relationships can be encoded as spatial constraints that the user wants the objects to meet, for example, that all logos need to be centre-aligned or that a group of photos should be positioned on a grid. As a frequent, yet cumbersome task, aligning and distributing graphical objects configures an interesting playground for exploring a very concrete type of spatial constraint in the creative activity of designing a document layout. Precisely positioning graphical objects in a layout is a task that pertains not only to designers, but also other professionals at work trying to create documents such as posters, slide presentations, or diagrams. Tools to support designers' practices in this context could potentially benefit a more general audience too. In particular, a tool that leverages the principles of instrumental interaction to support this type of spatial constraint could open a path for a family of powerful, yet simple tools that deal with more complex types of constraints in creative activities.

4 STUDYING SPATIAL CONSTRAINTS

This chapter explores the practices of designers and other professionals who lay out graphical objects in documents, and identifies the challenges they face.

Positioning objects in graphical layouts can be frustratingly time-consuming. Janacek et al. (1999) reported that an expert Coloured Petri Net designer spent over 60% of his time in a basic design task performing tedious and repetitive operations to reposition graphical objects. Mackay et al. (2000b) reported that *"expert users seriously underestimate how much time they spend on minor manipulations of the tool, especially those involving layout"*. These Petri Net designers estimated that they spent approximately 5% of their time on graphical repositioning, but video records showed that they actually spent closer to 30%. In order to check if these findings hold more generally and with today's graphical editing tools, I decided to study how professionals who create digital layouts as part of their work deal with alignment and distribution.

4.1 INTERVIEW STUDY ON ALIGNMENT AND DISTRIBUTION

Participants: I interviewed twelve regular users (ages 24-38; four women, eight men) of Adobe Illustrator, Adobe Photoshop, Sketch, Inkscape, Gimp, Corel Draw, Microsoft PowerPoint and Prezi. Half the participants (6/12) were professional designers (UX, product, and web designers); the other half included a software developer, a design student, a biologist, a political scientist, a geologist, and a computer scientist.

Procedure: I conducted critical object interviews (Mackay, 2002) in participants' offices or homes, inviting them to show me recent projects in which they had to lay out graphical objects. I asked them to recall specific problems, focusing on breakdowns (interactions that led to unexpected or incorrect results), innovations, and appropriations (the personal strategies they used, especially when dealing with breakdowns). I also encouraged them to show me these problematic tasks, and observed their reactions to mismatches between their expectations and the system's behaviour. The interviews were conducted in Spanish or in English, according to each participant's preference.

Data collection: I recorded the audio of the interviews, took written notes, and photographed the documents shown. Video recordings were shot over-the-shoulder to focus on participants' hands and the layouts being described.

Data analysis: For the interviews conducted in Spanish, I translated the data to English. With my collaborator Nolwenn Maudet, we used a thematic analysis (Clarke and Braun, 2014) approach to code the collected stories. We identified specific problems in each story and cross-checked them with the other stories. This provided us with a repertoire of the problems that participants face when aligning and distributing graphical objects.

4.2 RESULTS AND DISCUSSION

Participants used a range of strategies to align and distribute objects. Although all participants used the dedicated commands, many (8/12) also aligned and distributed objects *"manually"*. For example, they first used the mouse to roughly position the object, and then hit the arrow keys to visually fine-tune it. Participants view alignment and distribution commands as *"automatic"* operations, and treat everything else as *"manual"* operations, including the use of rulers (8/12), making visual comparisons within a zoomed-in area (7/12), and typing in coordinates (2/12). All the designers and one developer (P12) make extensive use of the keyboard to align and distribute objects, not only because it is faster, but also because *"there are too many options and menus"* (P3, UX designer) that clutter their screens and make them *"lose focus"* (P2, web designer). Most participants (8/12) use and appreciate the automatic guidelines that appear in some graphical editors as the user drags an a object: When a guideline appears, the user can snap the object to it by releasing the mouse, but the alignment is not persistent.

We identified three key issues that users face when positioning objects using current graphical authoring tools:

- Lack of *persistence*: The dedicated commands do not maintain alignments and distributions, forcing participants to realign or redistribute them after every minor change.
- Lack of *control*: Participants often cannot predict the results of the commands. Participants also lack tools for making and preserving minor corrections or *"tweaks"*.
- Lack of *generality*: Participants are limited to horizontal and vertical layouts when aligning and distributing objects.

PERSISTENCE

In command-based tools, applying an alignment or distribution command moves the objects but leaves no concrete trace of its use. Any change to one of the objects will likely require the user to reapply the command. This lack of persistence leads to the repetition of actions and hinders the reuse of previous results. For example, P5 (web designer) aligned two objects vertically: *"I wanted to move one to the right. I wish I could do it only in the horizontal axis, instead of being worried about introducing an offset in the vertical one. Some constraints are obvious to me but they are not captured by the tool, so it gives me more freedom than I need, and I have to realign"*.

The lack of persistence is closely related to the need of supporting repetitive not just one-time tasks. Optimising repetitive tasks requires some planning, such as creating auxiliary structures or guides, which is not worth it for most one-time tasks. P9 (computer scientist) explained that *"you need to have an idea of how the objects should look, and only then align with the commands, not the opposite; so you either plan everything in advance, or you reapply everything you did"*. P3 (UX designer) explained that *"for a one-time thing I do the job manually, but for a frequent task I find a tutorial to learn how to solve it with tools"*.

Many participants wanted to make the relationships among objects explicit, so they can be visualised, manipulated, and captured for later editing. Some used workarounds combining available tools, for example, half the participants reused a previous alignment or distribution by duplicating the objects and replacing them with new ones. P9 (computer scientist) applied this strategy although considered it to be *"cheating"*. P7 (political scientist) and P10 (biologist) wanted to know the distance between two graphical objects: *"The grid is not enough, I cannot count the squares"* (P7). P8 (geologist) needed to add tags to several pictures at the same position relative to their frames: *"I wish I had a way to declare this to the program"*. P9 (computer scientist) wanted equal spacing among items and created an *invisible spacer* — a transparent rectangle with the same height as the space he wanted to duplicate. Similarly, P11 (design student) created her own spacer by *"cutting the distance between two objects and pasting it between the rest of them"*.

CONTROL

The icons used to depict alignment and distribution commands appear intuitive, but participants still have difficulty predicting the results. P1 (designer) was trying to distribute objects and the outcome was not what he expected: *"It is not clear what will be the effect of the command, even if you have some experience with the tool. It is normal to have to undo and retry, sometimes it does not do what you want. See? This does not make sense to me. I am not even sure if I chose the right command"*. P9 (computer scientist) wondered: *"I am aligning with respect to what? Does the selection order matter?"*. P10 (biologist) had the same problem with distribution: *"What is the reference? Is it the width of the page?"*. P9 (computer scientist), after successfully aligning a group of objects inside containers, added: *"Now I was lucky, sometimes I have to undo and repeat the action, because it moves the element or the box. I have to be always alert, and do it in a precise mechanical way, always thinking of making the selection in the correct order"*.

Current command-based systems do not reveal how their algorithms work. Few highlight the alignment's pivot (the object used as a reference to align other objects to it) or the object's anchor (the reference point within an object used for alignment — usually the object's centre or a side), and even fewer let the user choose them. Users cannot predetermine if or how the selection order will affect the output. Half the participants told me that they did not feel in control and that they were frustrated by the commands, which some described as *"awkward"* (P12) and *"too automatic"* (P4, P5).

P5 described annoying limitations of the tool: *"There is a problem with hierarchy in layers and groups. Sometimes I cannot directly relate an object to one in another group, because they do not see each other; I have to ungroup and regroup so that the tool lets me align them"*. These breakdowns caused P10 (biologist) to completely lose faith in commands: *"Align vertically always makes a disaster. I do not trust it, so I do not trust align centres either"*. P12 (developer) also felt the lack of control: *"I have more trust in moving things manually because I find it more practical, I can put them exactly where I want"*.

To compensate this lack of control, participants appropriated the available tools. For example, P2 (web designer) needed to ensure equal spacing among a series of objects: *"I do not understand the distribution commands, so what I did was to cheat. I put one object next to the right side of the first one, I selected it and then pressed shift and the right arrow. I counted how many times I pressed the arrow, this gave me a kind of... procedural measure... of the space between the objects, that I memorised and then repeated for the rest"*. P10 (biologist) used a similar procedure, because *"it is safe"*.

Alignment and distribution commands use the geometric centre of objects, but sometimes this does not match the object's visual centre. Seven participants had recently used commands to align what they referred to as *"irregular"* or *"weird"* shapes, including icons, logos and text. All were forced to manually fine-tune the result to make it aesthetically pleasing. For example, P3 (UX designer), P5 and P6 (web designers) switched to a grid view and manually arranged each object's position. To our knowledge, current tools completely ignore these *tweaks*, so users must perform them manually after each use of an alignment or distribution command, therefore increasing the repetition of actions, preventing output reuse and increasing the likelihood of errors.

GENERALITY

Sometimes participants want to align objects along a diagonal, or shapes other than a straight line. They may also want objects, such as the arrows in a diagram, to remain parallel in spite of future edits. However, most current systems are limited to horizontal and vertical alignment and distribution[1].

P12 (developer) had to align text and images at different angles. Due to the lack of tool support he had to check visually if they looked right. Some participants came up with clever tricks to overcome this problem. P5 (web designer) was working on a wheel-shaped menu, with icons in the centre of each slice. He had to create an *"icons guideline"*, a layer with a grey circle that served as a visual guide to place the icons. This guideline can be seen as a reification of the relationship among the icons in the circular menu, i. e. a concrete object with which he could interact. P3 (UX designer), and P11 (design student) used similar strategies. P5 (web designer) puts his icons and labels inside transparent square containers that are larger than the icons, which he keeps aligned: *"The white space between an object and its square generates the illusion of space between two icons, but in reality it is a fake space, the containers are next to each other, so it is easy for me to locate them in regular positions. I have 100% control over what happens"*. P9 (computer scientist) described a similar strategy: *"Look at how I cheat. I create a fictitious box with a certain alpha, but not transparent, with a distinctive colour, very different from the background so it highlights and I remember it is not a real object. Then I centre each icon in its box, I group each pair, and I align the boxes"*.

1 The exceptions include tools that allow text to be wrapped onto custom shapes.

FROM ACTIONS TO RELATIONSHIPS: REIFYING ALIGNMENT AND DISTRIBUTION

Current commercial systems are procedural and lack explicit representations of alignment and distribution. When a user applies a command to align a set of objects, the user is telling the system that the objects belong together, that they are related in some meaningful way. Moreover, when a user applies a second command that affects some of these objects, for example, to create some sort of grid, the user intends the previous relationships to be respected. However, current systems have no memory or awareness of the context in which the task is being carried out: From its perspective, issuing a command is limited to changing the position of the selected objects. As soon as the command is applied, no trace is left behind of the constraint the user wants the objects to meet.

Current systems relegate alignment and distribution to, in the terminology of Wybrow et al. (2008), *one-way constraints*, isolated from other constraints in the layout and completely blind to their existence. This behaviour assumes that the user interacts with the layout at the object (or non-overlapping sets of objects) level, rather than as a whole with emerging, interacting properties that propagate effects to the rest. They are designed for the user to create spatial structures in an orderly, planned manner where interacting only once with the graphical objects is enough. I believe that these assumptions make it hard for users to organically grow and evolve the layout by exploring and discovering interesting visual patterns.

Current techniques do not reveal how their algorithms work, in particular, what are the rules to decide what will be the final position of a set of objects to be aligned (or distributed). For example for bottom-aligning, is the command applied relative to the position of a reference object? (How does this object get chosen? Could the user do it?) Of the one at the top, of the one at the bottom? Or based on an average of the selected objects' position? The user can only learn these idiosyncrasies by trial and error and, worse, the strategy varies across different software. This lack of transparency prevents users from predicting the results of the commands, and leads some to be afraid of experimenting with the layout, which may hinder creative exploration.

I argue that current systems oversimplify the tools they offer for alignment and distribution, either because they do not take into account the practices or real users, or because they want to avoid increasing the complexity of their software. In this study, I found that participants — particularly designers — do care about being efficient and finding elegant solutions to alignment and distribution: Some are even willing to invest time in following tutorials to optimise frequent tasks that are hard to solve with the tools at hand. Moreover, I observed that participants came up with clever tricks and appropriations when encountering obstacles, but some of them called them *"cheats"*: They perceived their solutions as not being *"right"*, yet they were determined to achieve their goal. This reveals the limitations of traditional commands facing both simple and complex users' practices that make them recur to using tools in unorthodox ways of which they are not always proud.

In addition, alignment and distribution in current systems are binary: From the system's perspective, a set of objects are either aligned or not, distributed or not, according to mathematical equations (e. g., a set of objects are centre-aligned horizontally if their centres belong to the same horizontal line), leaving no space for nuance. Existing systems use reference points for alignment and distribution that work correctly for "regular" objects, such as rectangles or circles, but that do not offer pleasant results for "irregular" shapes such as asymmetrical logos. Every time the user applies a command to this type of object, they need to manually tweak the special cases, as the system ignores this adjustment, no matter how frequent it may be. This uncovers another limitation of current techniques, which leave users positioning objects by eye with no system support.

Through this study, I found evidence that participants do want to make spatial relationships persistent, controllable, and more general: They do not perceive alignment and distribution as mere actions performed with procedural commands, but as spatial relationships establishing constraints among the elements of the layout, that deserve entity. I argue that alignment and distribution should be represented as first-class objects that users can manipulate directly. These new objects would then be persistent, and have their own settings and properties to be controllable, like other graphical objects. They could be made more flexible and powerful, for example to support circular alignments or non-linear distributions, without much complexity increase.

4.3 SUMMARY AND CONTRIBUTIONS

I interviewed 12 regular users of graphical editing tools about their practices to achieve alignment and distribution. This lead to the identification of three main issues that they face when interacting with current software: lack of persistence, lack of control, and lack of generality. Participants perceive alignment and distribution as relationships among objects, instead of just actions to be performed. I propose to reify these concepts into first-class objects that users can create, customise, control, and reuse.

5 SUPPORTING SPATIAL CONSTRAINTS

This chapter explores the reification of alignment and distribution into first-class objects that better match how users perceive relationships among visual objects when designing a layout. After reviewing the prior work on the topic, I describe the StickyLines *tool. I present two studies I conducted with it: an experiment with regular users of graphical editors and a structured observation with designers. Finally, I discuss how the design principles used in* StickyLines *support users in defining spatial constraints.*

The interview study in Chapter 4 allowed me to get a deeper understanding about the alignment and distribution practices of regular users of graphical editing tools. I observed the mismatches between their needs and what current tools offer in terms of defining and manipulating these types of spatial constraints. The study showed that users still struggle with the traditional alignment and distribution commands to create a variety of spatial structures, and would like the relationships among objects to be persistent, easier to control and more general.

I believe that a tool that leverages the principles of instrumental interaction to support this type of spatial constraint could open a path for a family of powerful, yet simple tools that deal with more complex types of constraints in creative activities.

5.1 CONTEXT

Early snapping techniques inaugurated the exploration of alignment and distribution in graphic design. Although the research literature has looked extensively at declarative, constraint-based approaches, most current systems commercially available involve imperative, command-based ones. Only a few have proposed the explicit reification of alignment and distribution, in the form of rulers and guidelines.

SNAPPING TECHNIQUES

As early as 1964, Sutherland's *Sketchpad* (1964) featured *gravity fields* to snap the cursor to nearby objects. *Snap-dragging* (Bier, 1990), based on a ruler and compass metaphor, creates transient "*alignment objects*" (points, circles and lines) inferred from the elements in the document — this could be considered a rather weak type of reification of alignment, or at least a first step towards it.

Snap-dragging has been extended by changing the motor space (Baudisch, 1996) and the user's velocity profile (Fernquist et al., 2011). More recently, new techniques have been introduced, for example, to keep objects aligned across slides with mixed-initiative approaches (Edge et al., 2015).

COMMAND-BASED TECHNIQUES

Virtually all current commercial software for graphical authoring, including Adobe Illustrator, InDesign, or Microsoft PowerPoint, provide menu-based commands for alignment and distribution. A recent technique, *GACA* (Xu et al., 2015), features alignment and distribution of objects in 2D (rows and columns) via a single operation if they are already roughly aligned. The system infers spatial relationships in the selected set of objects, without the need for manipulating 1D subgroups. However, command-based techniques do not persist relationships, and users often find their results hard to predict.

CONSTRAINT-BASED TECHNIQUES

Sketchpad was the first interactive tool to integrate constraints and direct manipulation. In most constraint-based approaches, e. g., *Juno* (Nelson, 1985), *IDEAL* (Van Wyk, 1982) and *Dunnart* (Dwyer et al., 2009), users declare constraints and the system computes a layout that satisfies them. When the system does not find any configuration that meets the constraints, it is not trivial to decide if such configuration actually exists, and when it succeeds, it is challenging to clearly guide the user during the change of state. Over- and under-constrained configurations can be particularly difficult for the system to solve, and the results can be difficult to anticipate. Some systems focus instead on constraint inference, such as *Chimera* (Kurlander and Feiner, 1993), *Pegasus* (Igarashi et al., 1997) and *Penguins* (Chok and Marriott, 1998). *DesignScape* (O'Donovan et al., 2015) automates *"the tedious parts of design"*, including alignment, by making layout suggestions based on a combination of user-defined and system-inferred constraints. Fewer systems, such as Xu et al.'s (2014) beautifier allow users to interact with the inferred constraints.

Wybrow et al. (2008) compared *one-way* and *multi-way constraints* for diagram editing. One-way constraints are easy to understand but limited: Constraints are broken when manipulating the objects involved, and an object cannot have more than one active constraint at a time. Multi-way constraints overcome these limitations, but make the system much more complex. Wybrow et al. concluded that alignment and distribution would be more usable if they provided *"truly persistent relationships*', which are only possible with multi-way constraints.

snapping and constraints combined

Briar combines *snap-dragging* with constraints (Gleicher, 1992a,b). Constraints are specified through augmented snapping, which takes the snapping location as an extra parameter to infer constraints. When snapping an object, the system reveals the new possible relationships to the user, who must choose among or reject them. However, the user cannot manipulate the constraints directly, and distribution is not supported. Similarly, *GLIDE* (Ryall et al., 1997) represents constraints with *"indicator"* objects. In *HyperSnapping* (Masui, 2001), snapping objects triggers the creation of constraints represented by square *"anchors"* at the snapping points, and the snapped objects temporarily become a group. Although it supports distribution and visualisation of constraints, these are not directly manipulable or persistent, as they are cleared when clicking outside the group.

reification of alignment and distribution

A few approaches have explicitly reified the concept of alignment into interactive objects. Raisamo's (1999) *"alignment stick"* uses a physical ruler metaphor to push objects. *Lineogrammer* (Zeleznik et al., 2008), a pen-input system for diagram editing, extends the alignment stick with a *"grabby ruler"* that collects objects when passing over them, and it supports distribution. However, while the stick reifies the action of aligning, the relationships themselves are neither directly manipulable nor persistent. In *Rock & Rails* (Wigdor et al., 2011), specific hand gestures represent relationships and help users align objects on a multitouch tabletop. In *Object-oriented drawing* (Xia et al., 2016), users can create persistent alignment relationships by linking the positions of graphical objects via *"attribute objects"*. *Magnetic guidelines* (Beaudouin-Lafon and Lassen, 2000) reify alignment relationships into persistent graphical objects that users can directly manipulate: Objects can be attached and detached from a guideline, and moving a guideline moves the objects attached to it. *Neat* (Frisch et al., 2011) adapted *magnetic guidelines* to a tabletop surface, and Beaudouin-Lafon (2004) introduced a version supporting distribution.

5.2 stickylines

Based on the analysis of study participants' practices (Chapter 4), we created *StickyLines*, a graphical editor with interactive guidelines for persistent, controllable, and generalisable alignment and distribution[1]. *StickyLines* features a canvas and a tool palette. Users can create standard geometric shapes, import images, and

1 I programmed the tool. Nolwenn Maudet collaborated in the design, under the supervision of Michel Beaudouin-Lafon and Wendy Mackay, who worked

move and resize them by direct manipulation. *StickyLines* reifies alignment and distribution into a category of objects called *stickylines*. Unlike current rulers that help users adjust objects by eye, stickylines are active relative to the objects, and can be easily manipulated and maintained. The design builds on top of the *magnetic guidelines* technique, which was introduced in the context of a Colored Petri Net design tool (Beaudouin-Lafon and Lassen, 2000). However, the capabilities were limited and not evaluated formally, and were not integrated into a general purpose tool.

I introduce *StickyLines* through a use scenario. To keep it simple and highlight *StickyLines*'s particularities, I focus on the positioning and scaling of graphical objects rather than on their creation and colouring.

USE SCENARIO

Terry is a graphic designer working on a poster for a talk about ecology. He has a big illustration of the Earth, several small illustrations of nature, energy, recycled products, and the organisers' logos. He wants to include the basic information about the talk (title, speaker, place, time, access), while keeping the text minimal.

In *StickyLines*, after importing all the images he needs, Terry creates a coloured circle in the centre of the page and positions the Earth's picture inside. He drags the small illustrations next to the circle and places some around it. He likes how it looks, so he decides to do the same for all the illustrations: He chooses the *ghost stickyline* tool from the palette to create an alignment based on the outline of the circle. He clicks on the circle and this creates a circular line around it. He drags the illustrations close to the ghost until they snap. Then he wants to distribute them evenly around the circumference, so he opens the ghost's palette and chooses the *distribute centres* option. The illustrations get positioned accordingly, and when pointing at the ghost, their centres are highlighted in red. He decides to change the location of one of the images, so he simply drags it to its new destination: As soon as he detaches the image, *StickyLines* recomputes the distribution with the remaining objects, and again when Terry drops the object in the new location. Terry feels that the illustrations are too close to the Earth picture so he drags the ghost to increase the offset. Since the objects are snapped to the ghost, they move with it as it gets resized. He realises that he can also make the ghost elliptical rather than circular, and plays with several shapes, until choosing one.

Then Terry positions the organisers' logos at the top of the page, roughly aligned horizontally. He chooses the *horizontal stickyline*

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closely with us in this project. A video illustrating the features is available at: https://ex-situ.lri.fr/videos/stickylines-video tool from the palette and clicks on an empty space next to the objects. A horizontal line appears and automatically snaps the logos that are close enough to it. Terry shortens it by grabbing a handle in one extreme, to make it more manageable. He wants to check how would the logos look at the bottom, so he drags the stickyline and drops it there. As he drags the stickyline, the logos move with it. He is still not convinced, so he will place them vertically instead: He opens the stickyline's palette and chooses the *reshape to vertical* option. This transforms the stickyline into a vertical one, respecting the relative positions of the logos on it. Terry places the vertical stickyline on the lower-left part of the page. Now he realises that one of the logos does not seem aligned to the rest: It is not symmetric on the vertical axis, so its visual weight is not in its centre. He clicks on the object and repositions it by hitting the right arrow key until he perceives the object aligns with the others. As Terry presses the arrow, a purple line appears at the original location and grows, showing the created offset: a *tweak*. Then he sees that another logo on the stickyline has the same problem, so he points at the first tweak, copies it, and the mouse pointer turns into a paste icon. Terry clicks on the asymmetric logo to paste the tweak, which repositions the logo accordingly. He thinks that the group of logos might look better on the lower-right part of the page instead, so he drags and drops the vertical stickyline there. The position of all the logos on the stickyline is maintained, including the tweaked ones. Next, Terry evenly distributes the space between the logos by choosing this option on the stickylines' palette. He notices that the space above and below one of the logos is too big: The logo is visually shorter and wider than the rest, but the image file is squared. To solve this mismatch, he resizes the logo's bounding box to match its visual extent, while the logo itself remains intact. As he adjusts the bounding box, *StickyLines* recomputes the distribution, reducing the space between the logos accordingly.

Later, Terry takes care of the text. He activates the *auto-create* tool in the palette, which will help him detect when two or more objects are aligned. He positions the title of the talk at the top of the page. Then he grabs the speaker's name and drags it close to the left extreme of the title. When *StickyLines* detects they are close to be left-aligned, it suggests a vertical stickyline, and Terry drops the name. The stickyline is created passing through the left border of the title, snapping both objects by their left sides, without moving the title. Now Terry drags the text block containing the time at the right of the speaker's name. *StickyLines* detects when the top of the object is close to be horizontally aligned to the speaker's name, and suggests the corresponding stickyline, creating it as soon as Terry drops the object. Next, Terry picks up the place, drops it on the same stickyline at the right of the time, and does the same for the block explaining how to reach the place. Terry resizes the horizontal stickyline until it matches the right extreme of the title, and then distributes the objects, quickly trying several options (left sides, centres, right sides) until he finds the one he likes. Finally, he moves the horizontal stickyline below to generate more space between the title and the details.

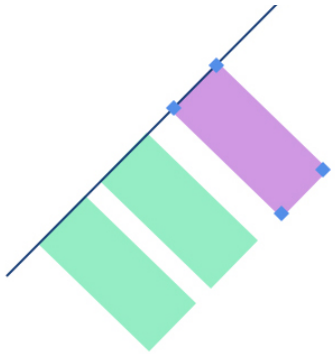


Figure 16: *StickyLines*: A parallel stickyline keeps objects parallel at any angle.

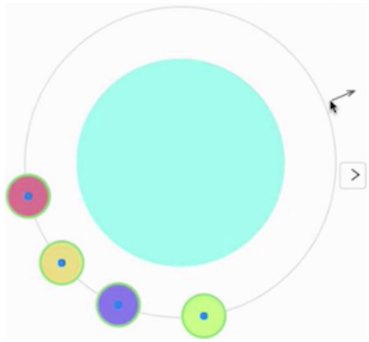


Figure 17: *StickyLines*: A ghost stickyline takes the shape of the object it surrounds.

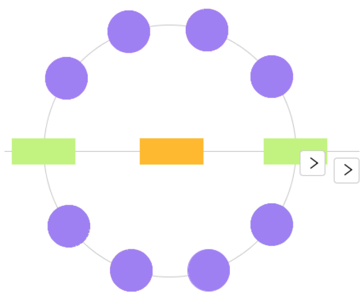


Figure 18: *StickyLines*: Simultaneous circular and linear alignments.

STICKYLINES

Users can create stickylines using five tools in the palette. For horizontal, vertical, circular and parallel stickylines, they simply click in the canvas and the stickyline appears. A parallel stickyline is a line at any angle that keeps objects parallel to each other, perpendicular to the line (Fig. 16). To create a ghost stickyline, users must click an object. The stickyline takes the object's shape and the user can adjust its offset (Fig. 17).

Dragging an object close to a stickyline highlights the snap point (centre or side) that would be used for alignment if it were dropped. Dropping the object attaches it to the stickyline at that snap point. Dragging an object away from a stickyline it is attached to detaches it.

Stickylines can be manipulated like regular objects: They can be resized, moved, and deleted. Moving a stickyline also moves the objects attached to it. Deleting a stickyline leaves the attached objects at their current position. A stickyline can be reshaped into another form and the positions of the attached objects adapt to the new form. Each stickyline has a button that opens a palette with additional tools, such as distribution and reshaping.

MULTIPLE RELATIONSHIPS PER OBJECT

An object can be attached to several stickylines by moving it close to them. When the cursor hovers over an object, the stickylines to which it is attached are highlighted. When the user creates or releases a stickyline near an object, the object snaps to it unless this breaks an existing relationship, i. e. unless the object was already attached to another stickyline and snapping it to the new one would change the object's position. This enhances predictability and reduces the chances of changing previous alignments and distributions by accident.

When the user moves a stickyline, the system tries to preserve existing relationships, but the stickyline being moved takes priority in case of conflicts. For example, moving the horizontal stickyline upward in Fig. 18 will detach the two rectangles from the circle once the stickylines no longer intersect. For added control, users can open a stickyline's palette and give it high priority, so that it is not overridden.

Users can also set the priority of an individual snap point by clicking on it and then on the star that appears (Fig. 19), or by just double clicking the snap point. In order to resolve conflicts when moving a stickyline, the system uses the most recent priority of each type of stickyline the object is attached to and of each snap point of the object. For example, if the object has both its left and right sides attached to vertical stickylines with high priority and the user moves one of them, the stickyline whose priority was set most recently will prevail. High priority relationships are displayed in orange, to help the user anticipate the system's behaviour. In addition, users can set a stickyline as "exclusive" in the stickyline's palette, so that its attached objects will ignore all other stickylines.

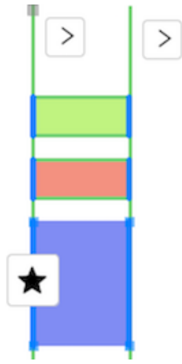


Figure 19: *StickyLines*: Prioritising a stickyline over the rest.

automatic stickyline creation and deletion

When "auto-create" is active in the tool palette, *StickyLines* detects potential horizontal, vertical and parallel alignments while objects are being moved, and displays dotted guidelines to provide transient feedforward. Dropping the object while this feedforward is visible automatically creates a stickyline.

When "auto-cleanup" is active in the tool palette, stickylines that become empty are automatically deleted, to avoid cluttering the screen. Users can also hide all stickylines from the tool palette. Hidden stickylines remain active: Hovering the cursor over an object attached to a hidden stickyline highlights the other objects on it; objects can be attached to a hidden stickyline by moving them close to it.

distribution

We found that, as with alignment, users want to distribute graphical objects according to different principles, and make these relationships persistent. For this reason, we included distribution as a capability of each stickyline. Users can select a distribution type from the stickyline's palette to distribute objects along the full length of an open stickyline or the perimeter of a closed stickyline. Options include equal spacing among objects or equal distances among reference points, e. g., left, centre or right for horizontal distribution. Reference points highlight when the cursor hovers over the stickyline or its attached objects.

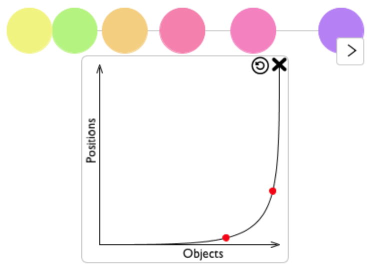


Figure 20: *StickyLines*: Non-linear distribution.

While the distribution is active, the layout is recomputed whenever objects are added or removed from the stickyline: The distribution is a persistent relationship between the attached objects. As shown in Fig. 20, users can also directly manipulate a curve that represents the mapping between each object and its position along the stickyline, making it possible to create a variety of non-linear distributions. This responds to need for generality that we found in the observational study.

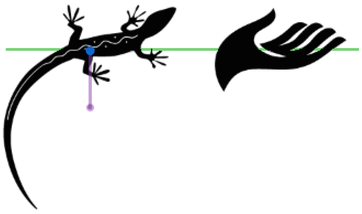


Figure 21: *StickyLines*: Tweaking the reference point (in blue) to align. The tweak is displayed in purple and can be edited, copied, or deleted.

Tweaking the reference point

In our observational study, most participants had to manually fine-tune, or *tweak*, the position of shapes such as icons, logos, and text, since the software they used did not align them correctly. In *StickyLines*, users can tweak the placement of objects attached to stickylines in order to correct an alignment when the visual centre of an object is not its geometric centre (Fig. 21), or to adjust the result of a distribution without modifying the position of other objects on the stickyline. Moving the arrow keys to "nudge" an object visually repositions it, even though the object remains logically attached to the stickyline. This offset, called a *tweak*, is recorded and displayed. The tweak is persistent: moving the stickyline preserves the offset. Tweaks belong to the objects so that if an object is detached from a stickyline, its tweak will be reused when attaching the object to another stickyline. Tweaks reify the action of adjusting an object's position, which is often needed when fine-tuning a layout. They are first-class objects that can be edited, copied onto other objects, and deleted. Tweaks are normally shown only when interacting with their parent object, but a tool in the palette lets users display all the tweaks.

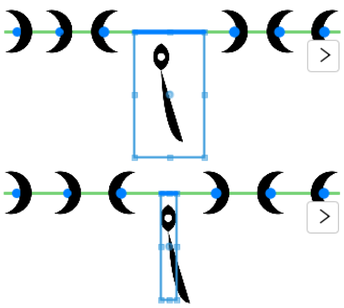


Figure 22: *StickyLines*: Tweaking the bounding box to base distribution on the visual extent.

Tweaking the bounding box

Similarly, participants had to repeatedly reposition objects after applying a distribution command, as sometimes the visual weight of an object did not match its geometrical dimensions. For this reason, in *StickyLines* users can also tweak the bounding box of an object to base distribution on its visual extent (Fig. 22), or to finely control its placement on a stickyline when it is attached by one of its sides. Hovering the cursor over an object displays its bounding box. The geometric bounding box is the default, but users can resize and move it through direct manipulation, without affecting the object itself. When hovering the cursor over a bounding box, its associated object is highlighted if the two do not overlap, to help the user find the object in case the bounding box is far from it. Moving and resizing an object moves and resizes its bounding box. Bounding boxes can be copied onto other objects, replacing their current one. Double clicking an object resets its bounding box to the default. In the same way as tweaking the reference point reifies adjustments to the object's position, tweaking the bounding box reifies adjustments to its extent.

5.3 SUMMARY

StickyLines explicitly addresses the problems identified in the interview study:

- stickylines and tweaks are persistent;
- stickylines and tweaks are visible and directly manipulable, enhancing user control over layout;
- stickylines offer more general support for alignment and distribution relationships and support tweaking to mediate between automated layouts and ad-hoc modifications.

I believe that besides facilitating the creation of complex layouts, *StickyLines* can encourage exploration of the design space in terms of spatial relationships. For example, a designer may first organise a graphical structure by creating some stickylines, populate them with objects and then play with the layout by moving the stickylines and tweaking the objects. To explore this question I conducted two studies: a controlled experiment to compare *StickyLines* to standard command-based alignment and distribution, and a structured observation of designers using *StickyLines* for a set of realistic tasks.

5.4 EXPERIMENT: GRAPHICAL EDITING TOOL USERS

A key feature of *StickyLines* is the use of guidelines to support alignment and distribution instead of the menu commands available in traditional tools, so we decided to run a controlled experiment to compare these two techniques. Since many of the novel features of *StickyLines* (such as tweaking, circular, parallel, and ghost guidelines) have no equivalent in standard tools and thus would give us an advantage, we chose to compare only horizontal and vertical alignment and equal distribution of space and reference points.

Our hypothesis is that stickylines are more efficient than commands when creating complex layouts, i. e. that they are faster and require fewer operations. For example, adjusting the horizontal position of a vertical alignment can be done by simply dragging the stickyline, while a command-based system requires grouping or selecting the objects and moving them — with the risk of losing a previous alignment or distribution. We expect the differences to be larger for more complex layouts, in which multiple adjustments are required. By contrast, if a given layout can be obtained by using an alignment command only once, a stickyline provides little advantage. It may even take more time to create the stickyline and attach the objects than to invoke a traditional

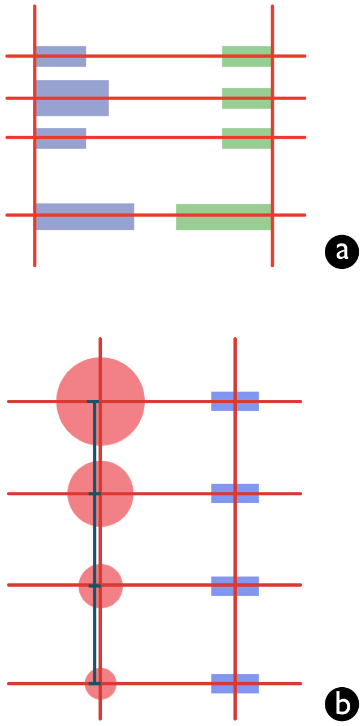


Figure 23: Experiment trial examples:
(a) easy layout;
(b) hard layout.

align command. The experiment attempts to determine whether or not this benefit is sufficient to provide a significant advantage in practice.

Experimental design: We use a [2x2] within-participant design with two primary factors: TECHNIQUE (*Command* or *StickyLine*) and DIFFICULTY (*Easy* or *Hard*). The two levels of difficulty (Fig. 23) are operationalised by the dependencies among the alignments and distributions to be created in a target layout. More precisely, we define a layout's optimal solution as the minimum number of actions (such as applying an alignment command, or attaching an object to a stickyline) required to complete it. To achieve the optimal solution, *Hard* tasks require performing the actions in a certain order, while *Easy* tasks do not impose a particular order. For example, the layout in Fig. 23b requires distributing the circles vertically, as indicated by the blue line, and only then aligning them with the rectangles on the right. By contrast, the alignments marked in red (Fig. 23a) can be performed in any order.

Participants perform three tasks in each of the four conditions, i. e. a total of twelve tasks. In order to avoid learning effects, we use two sets (*A* and *B*) of six layouts, each with three *Easy* and three *Hard* layouts. For each level of difficulty, layouts in sets *A* and *B* require the same number of actions. Sets *A* and *B* are counterbalanced by TECHNIQUE across participants. This ensures that participants are exposed to different layouts for each level of difficulty in each of the two TECHNIQUE conditions and for each repetition.

Participants: We recruited 12 participants (ages 22-34; five women, seven men) with normal or corrected-to-normal vision.

Apparatus: I created a Java application that supports command-based alignment and distribution similar to standard tools, as well as a subset of *StickyLines*' features, and it prompts the experiment trials to participants. Participants can use the mouse or trackpad according to their preference. The experiment was run on a 13" MacBook Pro running Mac OS 10.11.

The *Command* condition has a tool palette with six alignment commands (three horizontal and three vertical, one for each reference point), eight distribution commands (three horizontal and three vertical, one for each reference point, plus horizontal and vertical equal spacing).

The *StickyLine* condition has a palette with tools to create horizontal and vertical stickylines. Stickylines can be resized, moved or deleted, and objects can be attached or detached by direct manipulation. Users can activate or deactivate an equal distribution of space or reference points by choosing it from the stickyline's palette. None of the other features of *StickyLines* (feedforward, reshaping, distribution curves, etc.) are included. In both conditions, a reset button allows to start over from the initial position of the objects.

Procedure: Participants first receive a live scripted demonstration of the tool and practice the two techniques for five minutes. The DIFFICULTY conditions are grouped by TECHNIQUE and both factors are counterbalanced across participants. The order of techniques during practice is also counterbalanced across participants. Half the participants view set *A* for the first TECHNIQUE and set *B* for the second, the other half view layouts in the reverse order. Three replications of each DIFFICULTY×TECHNIQUE condition result in a total of 12 trials per participant. In each trial, participants are given a printout of the target layout showing the alignments and distributions (e. g., Fig. 23a) and are told to create it as quickly and as accurately as they can. In each trial, participants decide when to start and when they are done, by clicking on *start* and *done* buttons on the interface. At the end, they fill out a short online questionnaire. The experiment takes about 45 minutes.

Data collection: We collected data for $[2 \times 2 \times 3 \times 12] = 144$ trials. Measures include the *DURATION* of each trial in seconds and *#ACTIONS*, the number of elementary user actions such as move, align or create a stickyline. We also collected the responses to the questionnaire, a log of low-level mouse and keyboard events, and recorded the screen.

5.5 RESULTS AND DISCUSSION

Since both *DURATION* and *#ACTIONS* are strictly positive, we use a log transform of both measures in the rest of the analyses. The transformed dataset exhibits no outliers and is normally distributed. There is no significant effect of layout set (*A* or *B*) and no learning effect across repetitions. As we let participants use their preferred device (seven used the mouse and five the trackpad), we ran a t-test to check that the input device has no effect on *DURATION* ($t(116) = -0.44, p = 0.66$) nor *#ACTIONS* ($t(120) = -0.59, p = 0.55$).

An ANOVA[2] in the model *DURATION* ~ TECHNIQUE × DIFFICULTY × Rand(PARTICIPANT) shows significant main effects of TECHNIQUE ($F_{1,11} = 16.25$, $p = 0.002$) and DIFFICULTY ($F_{1,11} = 165.02$, $p < 0.0001$), and a significant TECHNIQUE × DIFFICULTY interaction ($F_{1,11} = 6.02$, $p = 0.032$) (Fig. 24). Post-hoc Tukey HSD tests show that *DURATION* is not significantly different between techniques for *Easy* layouts (59 seconds for *Command* vs. 48 for *Sticky-*

2 All analyses are performed with SAS JMP, using the REML procedure to account for repeated measures.

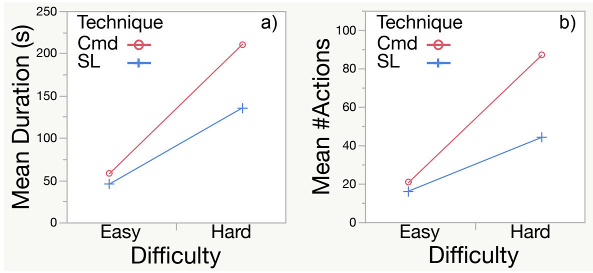


Figure 24: Experiment: Interaction effects between TECHNIQUE and DIFFICULTY for (a) duration and (b) number of actions.

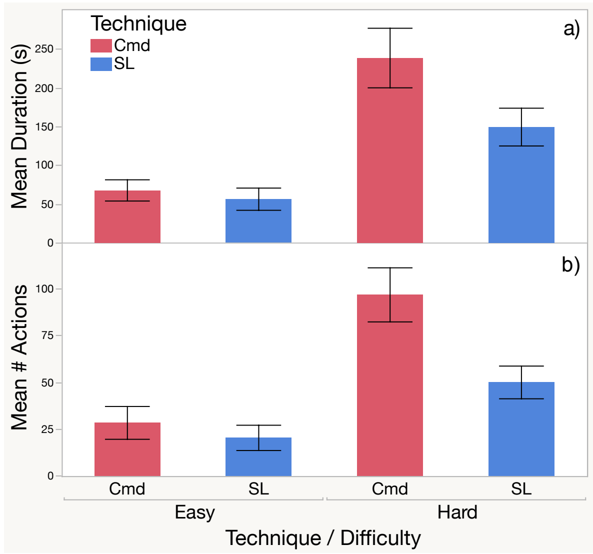


Figure 25: Experiment: Mean duration (a) and Mean number of actions (b) by TECHNIQUE × DIFFICULTY, with 95% confidence intervals.

Line), but is for *Hard* layouts (253 seconds for *Command* vs. 152 for *StickyLine*), supporting the hypothesis (Fig. 24a).

A similar ANOVA for *#ACTIONS* shows similar results: significant main effects of TECHNIQUE ($F_{1,11} = 25.95$, $p = 0.0003$) and DIFFICULTY ($F_{1,11} = 147.28$, $p < 0.0001$), and a significant TECHNIQUE × DIFFICULTY interaction ($F_{1,11} = 11.70$, $p = 0.0057$) (Fig. 24b). Post-hoc Tukey HSD tests show that *#ACTIONS* is not significantly different between techniques for *Easy* layouts (20.5 actions for *Command* vs. 16.2 for *StickyLine*), but is for *Hard* layouts (87.6 actions for *Command* vs. 44.5 for *StickyLine*), supporting the hypothesis (Fig. 25b).

The results highlight the effectiveness of *StickyLines* for complex layouts. They reduce the time for creating a difficult layout by approximately 40% (from 253 to 152 seconds) and the number of actions by 49% (87.6 to 44.5). However, the differences are much smaller for simple layouts, and are not significant. Although we expected that stickylines would be faster for complex layouts, we did not know if they would outperform alignment and distribution commands for simple layouts. This is because creating a stickyline and then dragging each object to it may take more time, with more actions, than selecting the objects and then the align command[3]. Nonetheless, the results suggest that stickylines are not detrimental for simple layouts.

The event log and screen recordings show that in the *StickyLine* condition, participants use stickylines extensively, allowing them to progressively create the layout. By contrast, in the *Command* condition, they use alignment commands more sparingly, and in fact they sometimes give up and create alignments purely visually. To assess the prevalence of this behaviour, we used the event log to count the number of times in which the last action applied to an object in the *Command* condition is a move as opposed to an align or distribute command, indicating that the participant assessed the object's final position visually. In 89.5% of the cases, the last action for a given object is an alignment or a distribution. In 4.9% of the cases, it is a move of a single object, i. e. a visual alignment. The remaining cases are ambiguous: 4.2% are a move of a group of objects and 1.4% are a constrained horizontal or vertical move of a single object, both of which may be used to maintain an alignment. By contrast, in the *StickyLine* condition, only two occurrences (0.4%) of final visual alignment of an object were recorded in the log.

In the post-hoc questionnaire, participants ranked stickylines as easier, more enjoyable and faster to use than commands, supporting the quantitative results. However two participants also found them more mentally demanding and one found them more frustrating. This may be due to a higher familiarity with command-based alignment or to some idiosyncrasies of my implementation. It may also be due to the fact that stickylines (without feedforward) can require more planning to create the proper structure, while with classical tools users often resort to visual, and therefore approximate, alignment.

5.6 SUMMARY

This experiment supports the hypothesis that stickylines are an efficient and powerful alternative to traditional commands. However, since it covers only a subset of *StickyLines* features, I also conducted a structured observation study to assess how professional designers use *StickyLines'* more advanced capabilities in a realistic setting.

3 After the experiment, I added a feature to select objects and snap them together to a stickyline in one action, which could further improve their efficiency, but it should be experimentally tested.

5.7 STRUCTURED OBSERVATION WITH DESIGNERS

I was especially interested in how designers would interact with *StickyLines* and appropriate its advanced features to create and tweak complex reusable structures, as this is likely to be the case when working on graphical layouts. With the collaboration of Nolwenn Maudet, I conducted a structured observation of expert use with six professional designers in order to capture their strategies. We chose structured observation (Section 1.2.4) as a method since we wanted to study the phenomenon without the goal of finding a cause-effect relationship.

Participants: We recruited six designers (ages 22-30; all women) with normal or corrected-to-normal vision, and two to seven years of experience. All were regular users of Adobe Illustrator and Adobe Photoshop, and some of Adobe InDesign (5/6), Sketch (3/6), Corel Draw (1/6), and Inkscape (1/6).

Apparatus: The version of *StickyLines* used in this study includes most of the features described earlier: horizontal, vertical and circular stickylines, distribution (of space or reference points), reshaping, tweaking reference points and bounding boxes, hiding/showing stickylines and tweaks. In order to keep the training time to around ten minutes and to avoid overwhelming participants with a number of features that are not at the core of the tool, we did not include parallel and ghost stickylines, and disabled feedforward, distribution curves, and automatic stickyline removal. Participants can use the mouse or trackpad according to their preference.

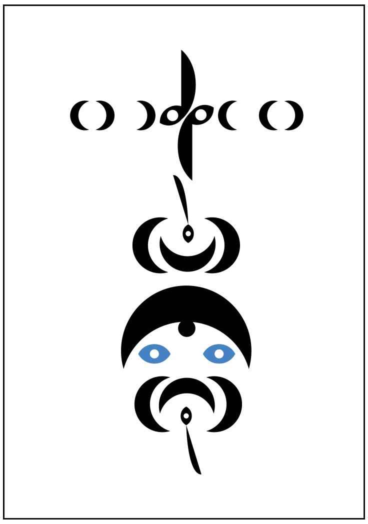


Figure 26: Structured observation: Portrait version of the poster to reproduce in the study.

Procedure: Each participant receives ten minutes of training with *StickyLines*, followed by two minutes of free practice. The study includes three tasks, and uses a think-aloud protocol. At the beginning of the first task, participants are given two printed posters and are asked to reproduce them using the predefined objects displayed on the screen (Fig. 26). They are told that each task builds upon the results of the previous one, including stickylines, tweaks and bounding boxes, unless they prefer to reset the layout. The posters include ambiguous alignment and distribution relationships, as well as "irregular" shapes, to encourage diversity in the solutions. In task one, participants reproduce the first poster. In task two, they can reuse the result of task one to generate the second poster, which is a similar layout, but with a different page orientation. Half of the users convert from portrait to landscape, the other half does the opposite. The first two tasks are not timed. In task three, participants have ten minutes to continue the series by designing two more posters that they would present to a client. The three tasks take approximately 45 minutes, after which participants complete a post-hoc online questionnaire.

Data collection: We recorded the screen, the audio, and took notes. We logged the interaction of the participants with the tool, and we collected the answers to the post-questionnaire.

5.8 RESULTS AND DISCUSSION

All participants relied extensively on *StickyLines* to construct their layout in task one and to adapt it later for tasks two and three — which highlights the power of providing persistent alignment and distribution. In task one, most participants (5/6) used the same strategy i. e. to *"first create a guideline for the main structure"* (P3) and later create secondary guidelines. For example P1 created a vertical *"base mark"*, roughly positioned all the objects, and only then added the other stickylines. By contrast, P2 first created all the stickylines she thought she would need before manipulating any object. She then *"collected"* objects by releasing a stickyline close to them, in sequence[4].

In task two, all participants reused existing stickylines, and P1 and P5 stated that they were useful. Participants also used *StickyLines* to verify alignment: P4 created a vertical stickyline close to two objects that were already positioned in horizontal alignments, to check whether or not they were also aligned vertically.

In task three, participants successfully designed creative variations to the prompted posters, as exemplified by Fig. 27.

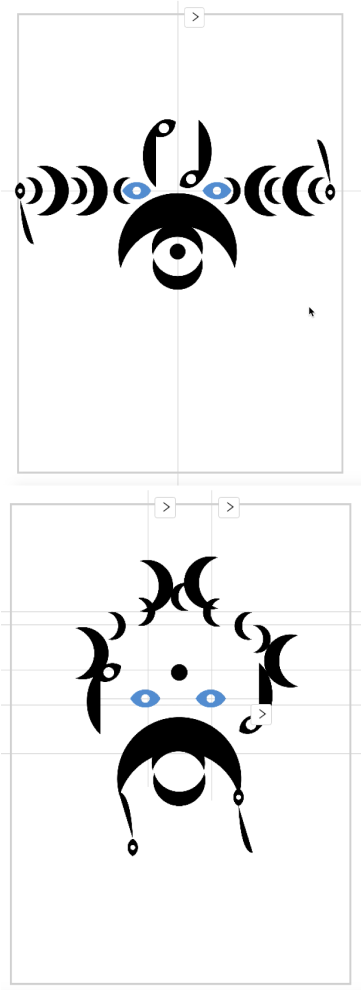


Figure 27: Structured observation: P1's poster variations in open-ended task three.

TWEAKS TO ADJUST AND MAINTAIN CUSTOM ALIGNMENTS AND DISTRIBUTIONS

As expected, most participants (5/6) tweaked object positions: All tweaked alignment and one (P5) also tweaked distribution. P1 based her strategy almost exclusively on tweaking reference points, barely using bounding boxes. Not surprisingly, participants created more tweaks in task one than in task two, indicating that they reused their previous tweaks. When converting the poster, P5 appreciated the persistence of tweaks: *"It helps that the tweaks are still there"*. Among the participants who created tweaks, some (3/5) edited them more often in task two than in task one. Only one participant copied tweaks (P2), in task three, which was more open-ended and exploratory. However, she pasted these two tweaks 16 times — a strong example of reuse. The low use of copying is probably due to the fact that the layouts required mirroring a tweak after pasting it, which was not supported by *StickyLines*, so participants decided to create new tweaks instead. More than half (4/6) expressed the need for a *"mirroring"* feature — which indicates they saw tweaks as graphical objects to act upon.

4 This was surprising, as we had not explained in the training that it was possible to "scoop" objects with stickylines.

Bounding boxes to adjust and maintain custom alignments and distributions

All participants also tweaked bounding boxes. P3 relied on this feature extensively and did not tweak reference points. In task two, participants reused tweaked bounding boxes more often than tweaked reference points: A majority of participants (4/6) copied bounding boxes and pasted them onto several objects, most during task one. Participants were not only interested in modifying the perceived borders of objects, but also their perceived centres. For example, P4 modified the bounding box to position its centre at the visual centre of the object. She then used this new point to attach the object to a stickyline.

Participants' use of both types of tweaking (reference points and bounding boxes) illustrate how *StickyLines* enhances control and generality over alignment and distribution, by making the tweaks persistent and editable.

Stickylines and tweaks as grouping mechanisms

Most participants (5/6) perceived stickylines not only as an alignment and distribution instrument, but also referred to them as "*groups*" or "*structures*". They appropriated tweaks to attach objects to a stickyline even if they were far away from it, in order to semantically group objects together. We refer to this as "*super tweaking*". For example, P3 explicitly used a stickyline as a grouping mechanism rather than as an alignment feature. She stated: "*I think of these four objects as a group, but this one is not on the guideline*", so she attached the object temporarily to be able to move the whole group by dragging the stickyline, and to remember that they belonged together, since she was planning to come back later to that part of the layout.

Most participants (5/6) resized stickylines to avoid overlapping other objects and manipulated each one as a small, compact group that they could easily move around. In task 3, half the participants (3/6) moved the stickylines out of the frame to build the new poster based on their current structures. Half the participants (3/6) hid the stickylines at the end of each task, to compare their work with the printout.

Stickylines as first-class objects

Participants used stickylines extensively during the three tasks. For the second alternative poster in task three, all participants manipulated the position and type of the stickylines more than the objects themselves, supporting the idea that participants perceive stickylines as first-class objects, i. e. entities with which they can interact as with any other objects of interest.

In fact, participants asked for even greater levels of interaction with the stickylines. For example, one participant wanted to *"capture the distance between two guidelines in order to reuse it"* (P1), and two participants said that they would like to align and distribute groups of stickylines as if they were regular objects (P1, P4). P4 wanted to cut a line in two parts, since her *"two groups [were] on the same line"* (P4). Half the participants (3/6) also wanted to be able to merge stickylines. Some participants wanted to know if an object is at the centre of a straight stickyline (2/6), to move stickylines precisely with the arrow keys (2/6), to move multiple stickylines at once (5/6), to copy a stickyline to reuse its length (1/6), to snap the centre of a bounding box to the centre of its object (1/6), to reveal all the bounding boxes in the layout (1/6), and to draw the stickylines themselves to define their initial length (1/6). These suggestions demonstrate the power of using stickylines to reify layout relationships, and merit future exploration.

PARTICIPANTS' FEEDBACK

At the end of the study, we asked participants to compare *StickyLines* with their usual tool for creating posters. All participants stated that *StickyLines* was as or more enjoyable than their usual tool, over half (4/6) that it was more powerful and more flexible, and half (3/6) also found it easier to use. P4 stated: *"As with any tool that I have learned, I need time to get my bearings and acquire habits"*. One participant ranked *StickyLines* as less precise than her usual tool because she would move an object's bounding box accidentally when trying to move the object[5]. Three participants found *StickyLines* more mentally demanding. P5 clarified: *"For now, StickyLines is more demanding, but it is also because I am learning it, but [it is] much more powerful and interesting"*.

5.9 SUMMARY

This study demonstrates that designers can quickly learn to use *StickyLines* and adapt their work practices to take advantage of stickylines and tweaking. It supports the findings from the interview study about the value of supporting persistence, control and generality to extend the power of tools for graphical layout. This structured observation also reveals examples of spontaneous appropriation, such as super tweaking an object's position in order to attach it to a distant stickyline.

5 The study version did not support zooming.

5.10 DISCUSSION: DESIGN PRINCIPLES

5.10.1 *Reification*

A stickyline is an instrument that reifies the action of aligning a set of objects into a noun — an alignment relationship. It establishes a persistent spatial constraint among the objects, one that can be interacted with, controlled, and tweaked. As such, it is not a passive element in the user interface, but an active constraint source that acts upon the objects, enforced by the system in a way that is constantly revealed to the user.

Support for diverse design strategies

Stickylines do not impose a certain order in the design process. The user may start with constraints and then take care of content, do the opposite, or a mix.

- *Constraints first:* An empty stickyline is still an explicit representation of a constraint that a user can visualise and think with. Empty stickylines let the user plan a structure that will get populated with objects once it is stable — as in P2's strategy during the structured observation study.
- *Content first:* The user might play with the objects' positions and once they like a particular spatial configuration, create stickylines to persist the existing relationships and make them more precise.
- *Mixed order:* Another strategy, employed by several participants in the structured observation study, consists of using stickylines to build scaffoldings where objects are laid out progressively: the structure is assessed and modified by creating, moving, resizing, reshaping, or deleting stickylines. In addition, the system can infer alignment relationships and suggest them to the user, as the user interacts with the graphical objects. Given that the system detects straight alignment as well as parallelism at any angle, this might allow users to discover interesting possibilities. Feedforward suggestions can always be ignored or deactivated altogether. This is an example of both discoverability[6], and co-adaptation (Mackay, 1990), as the user adapts the content to the constraints proposed by the system, and also adapts the constraints by controlling and tweaking them.

6 As in Octopocus (Bau and Mackay, 2008), where feedforward guides are prompted to the user to assist them in the generation of new gestures.

In *StickyLines*, an alignment or distribution constraint can be devised *a priori* by the user, it can be created by the user *after* interacting with objects, or it can emerge *during* the manipulation of content, discovered by the user or prompted by the system.

Collaboration potential

Leaving traces of interaction through the reification of spatial constraints is not only useful to scaffold the design while creating a layout, but also to reveal its underlying structure. This may facilitate the collaboration with the user's future-self (for example, to reuse the structure as a template in a new document) or with colleagues (to visualise the decisions that each collaborator made). Moreover, stickylines could be used by design professors in handouts, to show examples of structures to students. A further enhancement to *StickyLines* could consist of opening an existing layout and running a constraint discovery process where the system reveals the constraints it detects, so the user can decide whether to use the proposed stickylines to continue editing the layout.

Instruments as objects of interest

Because we offer an explicit representation of alignment and distribution through reification, participants quickly interact with stickylines as with any other object in the layout. The division between instruments and objects of interest (OOI) gets blurred: The stickyline instrument becomes an actual OOI when the user is interacting with it. This interaction is simple because it builds on the user's experience with other graphical objects: e. g., handles to resize, direct manipulation to move, delete key to delete. Moreover, users do already take advantage of OOI as instruments in ad-hoc ways (as in P1 and P9's *"spacers"* in Chapter 4). *StickyLines* is an example of how we can design instruments that incorporate this duality while offering extra capabilities, in order to achieve more power without much more complexity.

As the user focuses sometimes on the content and sometimes on the spatial constraints, it is fundamental that key spatial constraints are reified entities whenever possible, and not just the temporary consequence of performing an action. Spatial constraints must be visual, interactive, persistent — true objects of interest. They not only remind the designer of the decisions they made: They are instrumental in the making of those decisions.

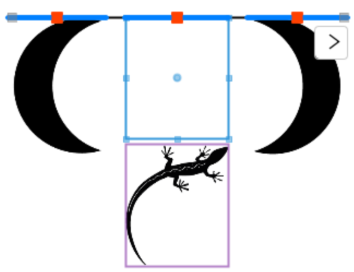


Figure 28: Using a super-tweaked bounding box as a placeholder for distribution.

Personalisation of creative constraints

Structured observation participants who appropriated tweaks to keep far away objects on the same stickyline, did so because they considered these objects as part of a group that they wanted to keep together. Similarly, one designer in a pilot study that I ran before the structured observation, left the bounding box of an object attached to a stickyline as a placeholder for horizontal distribution, but placed the actual object where they wanted, considerably below the stickyline (Fig. 28 shows a reconstruction). These examples illustrate how *StickyLines*, via tweaks and bounding box manipulations, breaks the binary nature of alignment and distribution. It reifies ad-hoc adjustments that users apply to the objects because *they know better than the system*. It allows users to redefine the concept of alignment and distribution, and to incorporate, to some extent, their personal style in terms of visual perception.

5.10.2 *Polymorphism*

A stickyline is polymorphic by design: As it is aware of the objects attached to it as well as their properties, applying an instrument to a stickyline could apply the instrument over all the attached objects. For example, a colour instrument could be applied directly to a stickyline in order to colour all its attached objects. The colouring could affect only current objects, or also the future ones[7]. Besides saving the user from having to paint the objects one by one, such a feature would allow them to think about categories of objects, rather than individual ones. We can easily imagine other kinds of instruments that could be applied polymorphically in this context. For example, a persistent bounding box instrument that the user creates with a certain size and drops on the stickyline to resize all the elements. The instrument would be kept by the stickyline, and be accessible for the user to later modify the preferred size by direct manipulation, affecting all the attached objects.

5.10.3 *Reuse*

In Chapter 4, I showed that half the interviewees had reused a previous alignment or distribution by duplicating the objects and replacing them with new ones — which reveals their need for reusable structures. Reification is the first step to make content and constraints reusable. Once a concept is reified, thus visible

7 The latter could be done by, for example, having a persistent colour property in the form of a colour swatch inside the stickyline's palette; the stickyline itself could be displayed in that colour to remind the user of the active constraint when the palette is hidden.

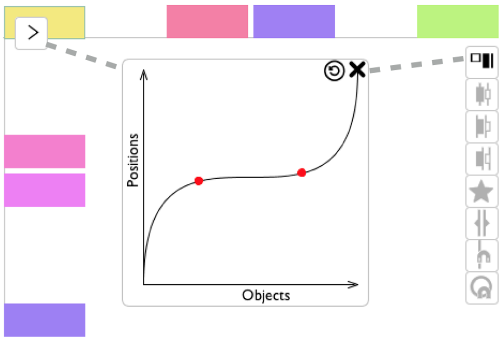


Figure 29: Two stickylines share the same distribution curve.

and interactive, the interaction can be made stronger by, for example, supporting copying and pasting, or enabling the modification of a wider range of its properties. For example, a *priority* relationship between an object and a stickyline could be copied and pasted to other objects that should align using the same logic. A single *distribution curve* could be attached to multiple stickylines, so that they share the same type of distribution, and subsequent changes in the curve propagate to all the related stickylines (Fig. 29).

5.10.4 *Substrates*

A group of stickylines on the canvas forms a substrate. Each stickyline is aware of the others, and all the constraints in play interact with each other. The system keeps a global knowledge of stickylines, graphical objects, tweaks, bounding boxes, and priorities, so that the user's input changes the layout accordingly. The substrate is exposed to the user: Existing constraints are visible, rules are explicit, and there are no hidden algorithms. On a smaller scale, one single stickyline also constitutes a substrate, as it embeds the user's personal rules on alignment, distribution, relative positions among objects, tweaked positions and bounding boxes. By building this type of spatial substrate, users can define and manipulate their own creative constraints related to alignment and distribution. Supporting substrates that flexibly match how users actually grow out a layout, makes the system's responses easier for them to predict and understand, and renders the interaction much more powerful.

5.11 PUSHING STICKYLINES FURTHER

More general structures could be supported if we push the *StickyLines* approach further. For example, the user could create a free-form shape stickyline by drawing any shape, directly on an empty canvas, or using a base shape as a model, by drawing upon its contour. A ghost stickyline currently works for geometrical shapes, but it could be extended to any shape, as long as it is vectorised or has a transparent background[8]. Stickylines could be rotated[9], which would facilitate the creation of structures with diagonal alignments. They could also be mirrored, for example, via a dedicated instrument that mirrors any object it is applied to (i. e.combining reification and polymorphism). Other spatial relationships could be inferred, for example, detecting when two objects are concentric[10].

Composite constraints could be defined and manipulated by the user. Currently, a stickyline's position can be directly manipulated, making it easy to work with groups of related objects, without having to use the traditional grouping mechanisms in most systems, which do not allow objects to belong to multiple groups. Moreover, dragging the intersection of two stickylines, for example, a vertical and a horizontal, moves both and all the objects attached to them, facilitating the edition of grid-like structures. One possible enhancement could be to lock the intersection to establish that two or more constraints belong together and should be treated as one composite constraint (Fig. 30). So, for example, moving either would move the others too, respecting their relative positions. This could be used to create more complex structures.

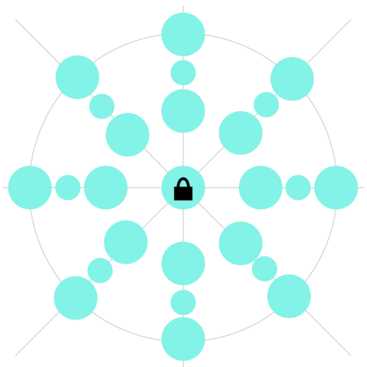


Figure 30: Multiple stickylines locked to form a composite constraint, which could be duplicated to create more complex structures.

In a more general scenario, outside of graphical editing tools, and beyond spatial relationships, stickylines could be used as more general instruments for semantic grouping, ordering, or filtering. For example, file icons on the desktop could be snapped to a stickyline that orders them by size (a weight metaphor could be used: heavier files could make the line go down, as clothes on a string), last modification date, etc. Dropping a script file on a stickyline could run the script with the attached files as a list of arguments. Of course, this would imply breaking the application silos and having access to native OS capabilities, but I believe it is worthwhile considering.

8 Ideally with an alpha-channel, otherwise the system should perform a more sophisticated edge-detection.

9 In the current version, only parallel stickylines rotate.

10 I programmed a feature that detects this type of relationship, shows a cross in the shared centre, and snaps objects to other objects' centres. However, a proper reification of this relationship that is suitable for subsequent interaction is still to be designed, so I did not include it in the user studies nor in the system's description.

5.12 SUMMARY AND CONTRIBUTIONS

I built *StickyLines* to provide persistent, fine-grained control over alignment and distribution, as well as more general capabilities, such as the creation of circular, parallel, and shape-adapted configurations, and the tweaking of an object's position or bounding box. I conducted a controlled experiment demonstrating that, for complex layouts, *StickyLines* is up to 40% faster than standard commands and reduces the number of actions by up to 49%. I also ran a structured observation study that showed how professional designers can quickly adapt to and appropriate *StickyLines*. *StickyLines* relies on the reification of alignments and adjustments, turning them into first-class objects that users not only learn to use efficiently, but also want to push further. *StickyLines* supports users' diverse design strategies: starting with constraints and then taking care of content, doing the opposite, or a mix. *StickyLines*, via tweaks and bounding box manipulations, breaks the binary nature of alignment and distribution, allowing users to incorporate their personal style. The *StickyLines* approach illustrates how the design principles in instrumental interaction plus substrates can be used to support spatial constraints by turning them into true objects of interest.

Part II

CONSTRAINTS IN CONTEMPORARY CHOREOGRAPHY

In this part of the dissertation I go beyond spatial constraints, seeking to support the definition and manipulation of spatial and temporal constraints. I focus on contemporary choreography, an art form involving three dimensions, time, and a rich variety of constraints stemming from bodies, metaphors, movement qualities, and marked by the creative collaboration between choreographers and dancers, who reinterpret and shape these constraints. In Chapter 6, I study the current practice of contemporary choreographers to have a better understanding of how do they express choreographic ideas in their creative process. Based on the results, in Chapter 7 I address the definition of spatial and temporal constraints through Knotation*, a digital tool for choreographers. In Chapter 8 I study collaboration in choreography when mediated by* Knotation *in real-world settings.*

Like designers, choreographers need to deal with spatial constraints, as dance happens in space. However, these constraints are inherently more complex, as the human body moves in 3D over time. An iconic example is Martha Graham's solo *Lamentation*, from 1930: She wore a loose tube of stretchable fabric (Fig. 31) so that the curves, lines, and surfaces created by her movements inside the tube enhanced the audience's perception of the relationships between body and space (Au, 2002). On top of spatial constraints, choreographers have to contemplate a range of movement characteristics, such as intention and dynamics. Some contemporary choreographers also make use of metaphors and movement qualities, which imposes additional constraints that are more subtle and oftentimes harder to explicitly articulate. In addition, contemporary choreographers work closely with dancers, so they need to consider the interplay between dancers and constraints. Because dancers have agency, they can interpret and redefine the constraints.

Figure 31: Martha Graham in *Lamentation*. Source: Moselsio, H. Library of Congress, https://www.loc.gov/item/ihas.200154217/.

Unlike designers, contemporary choreographers seldom have access to digital tools specifically designed for choreography. I am fascinated by the potential of developing a partnership between choreographers and technology. This presents a major design challenge because the choreographic process is complex, idiosyncratic, and highly diverse. Choreographers lack a common method for representing dance. Instead, they rely primarily on their individual and collective memory to link their ideas and document their work. Formal systems such as Laban (1948) or Benesh (1977) notations are used mostly by big dance companies who can afford a full-time notator. Contemporary choreographers rarely use these systems, because they are designed to document finished work and are cumbersome to deploy, thus not suitable for early exploration phases.

Some contemporary choreographers do adapt physical and digital technologies to meet their individual approaches and needs (deLahunta et al., 2004; Birringer, 2002). However, although many capture intermediate phases of their work with video, few incorporate interactive technology as a fundamental part of their creative process.

My goal is to provide ways for choreographers to express and manipulate a variety of creative constraints through technology that can be integrated in their creative process, rather than seeking to replace their current practices. However, we still lack a deep understanding of how do these professionals manage their ideas, what type of digital and analogue tools they use, and how.

6 STUDYING THE CREATIVE PROCESS

This chapter examines the creative practices of contemporary choreographers: How do they capture their ideas and how do these evolve? What kind of artefacts do they generate? I propose the Choreographic Object-Operation *theoretical framework, which articulates the emerging patterns in these idiosyncratic practices, and I derive implications for design. I then use the framework as a prompt for choreographic activities in an observational study with professional choreographers and dancers.*

I was interested in creating technology to support the early creative phases of choreography, as well as the evolution of choreographic ideas over time. I wanted to enable choreographers in defining and manipulating spatial and temporal constraints that shape the content in their dance pieces. To design such technology, I had to first understand how choreographers imagine, create and concretise their ideas, both with and without technology support.

6.1 CONTEXT

CONTEMPORARY DANCE

The main medium in contemporary dance is movement, *"deliberately and systematically cultivated for its own sake, with the aim of achieving a work of art"* (Stevens et al., 2003). The source of a choreographic idea can reside in any modality (e. g., visual, auditory, tactile, emotional, verbal), but is later expressed through movement, tension, and stillness (Stevens, 2005b). Creativity in contemporary dance is movement-based, as material is developed through experimentation and exploration in the medium itself (Stevens, 2005b). Thus, the creative search is literally embodied (Stevens et al., 2000; Kirsh et al., 2009). As put by Beiswanger (1962), *"dances are not merely performed by dancers; they are composed upon the bodies of dancers"*.

Like temporal arts (such as music and poetry) dance happens in time, but the experience of the audience is predominantly visual. But unlike visual arts (such as painting and sculpture), the product of dance is not a static object (Stevens, 2005b). Dance is *"communicative and expressive; it is visual, spatial, temporal, kinaesthetic, sensual, evocative, affective, dynamic, and rhythmic"* (Stevens et al., 2003). All these components plus the interaction between dancers carry a huge amount of information to process for observers, dancers, and choreographers (Wechsler, 1997b). From a cognitive perspective, contemporary dance constitutes a highly complex case, involving short- and long-term memory, multi-modal imagery, learning, performance, and expressive communication (Stevens, 2005a). In addition, in the context of postmodernism, contemporary choreographers have found new creative ways of using materials, non-movement elements (e. g., speech, video, props), and non-traditional spaces (such as the theatre lobby), adding the coordination of these elements to the overall challenge of a dance production (Morris, 2005).

Studying contemporary dance is difficult due to its ephemeral nature, the scarcity of traces of the work's progress, and the lack of records of its performance that capture all its relevant aspects (Stevens et al., 2000). Moreover, video can only capture a particular company's interpretation of a piece, rather than the *"original conception of the work"* (Noll, 1967).

THE CREATIVE PROCESS

When creating a dance piece, contemporary choreographers start from a particular stimulus, from which they develop a generative idea to explore (Schiphorst et al., 1990). Dance pieces can be based on a personal experience, nature, literary works, chance, or on anything that motivates or inspires the choreographers (Morris, 2005). Choreographers may go to the studio with no clear idea of what will be their source of inspiration: Instead, they often create and resolve tension guided by their intuition and past experience (Morris, 2005). The choreographic creative process is both interactive and iterative: Schiphorst et al. (1990) described how each choreographer *"interacts with the idea, shaping it and being influenced by it, in a cyclic evolutionary process."* In this sense, choreography could be analysed as a design activity (Beiswanger, 1962) — and in fact, some choreographers actually see their creative process as problem solving (Morris, 2005).

Contemporary choreographers are highly skilled professionals who develop their own set of methods and styles, while constantly seeking for novel forms of creative expression. Their creative processes are intentionally unique, which makes them reluctant to adopt tools that enforce another choreographer's creative practice. Each piece is informed by the choreographer's implicit knowledge, which also affects the decision-making process and shapes both individual dance productions and the field of dance as a whole (Blom and Chaplin, 1982). What is more, contemporary choreographers sometimes explicitly challenge the field's rules and their own ideas and ways of working, drastically modifying their approach from one project to the next (Blom and Chaplin, 1982; Groves et al., 2007; Morgenroth, 2004; Weiss, 2018).

6.2 INTERVIEW STUDY WITH CHOREOGRAPHERS

My first step was to interview choreographers and build upon the higher-level commonalities in their implicit, complex, and highly creative craftsmanship. My goal was to identify and understand the elements they manipulate as they create a piece and how these elements evolve during the choreographic process.

Participants: I interviewed six professional choreographers (ages 24-47; five women, one man). They had between 2 and 20 years of experience (median: 6.5). At the time of the study, two participants were the directors of their dance companies, and the rest worked independently, collaborating sometimes with other choreographers or music composers. Half were based in France and half in Argentina.

Procedure: Whenever possible, I interviewed participants in their homes or dance studios, to have easier access to their artefacts and materials. Each critical object interview (Mackay, 2002) lasted for approximately one hour and a half, and was conducted in French or Spanish, according to the interviewee's preference. I asked each participant to choose a recent piece that they had choreographed, either current or complete, and to describe their creation process, step by step. I invited them to show me the artefacts they used to explore or capture ideas, including notebooks, video, and digital files. I probed for specific stories, sparked by their choreographic artefacts, in order to help them provide a grounded reconstruction of the details.

Data collection: I recorded audio, photographed the choreographic artefacts, and took hand-written notes. I also filmed the participants who explained dance fragments by dancing or marking.

Data analysis: I first translated all the raw data to English. I used a thematic analysis (Clarke and Braun, 2014) approach with Sarah Fdili Alaoui to code the collected stories. With my two advisors, we revised the results of the coding and used them to construct six themes: *choreographic objects*, *creative phases*, *representations*, *operations*, *specificity*, and *focal points*.

6.3 RESULTS AND DISCUSSION

In this section, I refer to participants as P1-P6 but I credit each choreographer when I present images of their intellectual property, specifically their personal notes, scores, and choreographic notation.

All participants chose pieces with a contemporary dance approach, with diverse contexts and initial constraints. P1 created a tango that is strongly influenced by contemporary dance elements. Although tangos are typically performed in pairs, this dance involves a solo performer, who interacts with a musician on stage. P2 choreographed a piece for two dancers who interact with a piano by dancing on it and generate sound by hitting its surface. P3 designed a piece for a group of dancers whose bodies represent stone fragments that evolve in space and time. A key challenge for P3 was to make the work fit within a larger performance that included choreographies based on several different dance styles. P4 created a dance for a theatre play, constrained by the script and the choice of traditional children's games. P5 choreographed a piece for over 100 non-dancers within a public installation. P6 designed a piece inspired by yoga and meditation techniques that explores how body and mental states can generate movement, sustained in time. Only two choreographers (P3 and P5) worked with predefined music; the others collaborated with a music composer.

CHOREOGRAPHIC OBJECTS

Choreographic objects represent choreographic ideas that are manipulated throughout the entire process. Participants formalise them at various levels of abstraction and detail, at times in their own minds, in the dancers' bodies and memories, or captured via paper, video, or other support tools. For example, P6 began a piece inspired by the concept of *"beatitude"*, and P1 transformed the traditional two-person format of a tango into a solo. Each used a different strategy to explore the initial choreographic object: P6 defined very specific constraints for determining how the movement would develop, whereas P1 improvised by pretending to dance with an imaginary body in the room. Eventually, P6 abandoned the idea of beatitude but continued working under the initial constraints to generate the score of the piece. P1 added other *"guidelines"* to generate movement material and compose sequences, typically linked with metaphors and feelings. Even though the details of each strategy varied greatly, we found that all participants began with an initial idea or set of ideas, which generated the elements that formed the final choreographic piece, similar to Schiphorst et al. (1990). Figure 32 shows representations of several types of choreographic objects: Inspirational symbols and high-level concepts (Fig. 32a), constraints (Fig. 32b), and concrete dance sequences (Fig. 32c).

The concept of choreographic object, though it is not a standard term in dance, has a few parallels in the literature. For example, one of the central points in *Synchronous Objects* was to reflect on how choreographic ideas could be expressed, and exist, in durable media other than the body (Palazzi and Shaw, 2009). For Forsythe, choreographic ideas in the form of *"choreographic*

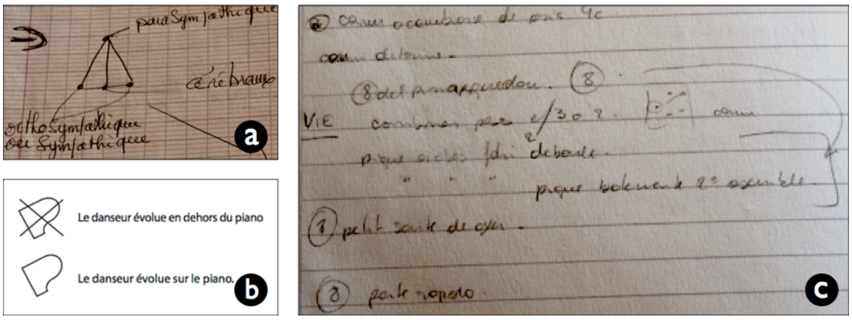


Figure 32: Interview study: High-level choreographic object (Myriam Gourfink) (a). Spatial constraint for movement, from *"Collision hétérogène"* (Amandine Bajou and Marc Garcia Vitoria) (b). Dance sequence for a group of dancers (Fernanda García) (c).

objects" encourage choreographic thinking, rather than replacing the body (Weisbeck and Forsythe, 2008). Similarly, deLahunta and Pascual (2013) talk about *"pre-choreographic elements"*, belonging to a *"pre-phase of choreography"* in which content is created and tested but not yet selected or ordered. They refer to *"specific (moving) ideas or concepts"* that appear consistently throughout the piece.

A few (2/6) participants articulate their work using well-known dance vocabulary, such as postures, phrases, sequences, scenes. The others occasionally use these terms, but more often focus on the piece as a continuous sequence of movement with identifiable *"moments"*, *"states"*, or even *"colours"*, rather than discrete parts with a beginning and an end.

Famous choreographers also have their personal way to parse their choreographies, which far from being fixed, depends on each piece and their own intentions. For example, Anne Teresa de Keersmaeker sometimes organises movement in *"cells"* according to the *"principle"* by which they will be sorted out in *"series"*. These series can overlap, forming higher-level blocks of units (De Keersmaeker and Cvejic, 2012). Other times, and even for the same piece, she organises movement at a phrase level, where each phrase has a *"qualitative attribute"*. In addition, in some of her choreographies the small units are rather short motifs linked to musical themes. Another example can be found in deLahunta and Barnard (2005), where Wayne McGregor and dancers participated in a parsing exercise: The choreographer parsed only a few units of his interest, leaving many segments of movement unparsed.

Participants sometimes use temporal references to refer to their choreographic objects: P4 talks about a *"sequence that goes from beats 1 to 16"*, while others use spatial references: P3 refers to *"the part in which the dancers are in a round"*. Some participants name their objects with criteria ranging from distinctive visual characteristics: P1 had a *"duck feet posture"*, metaphors: P1 dances

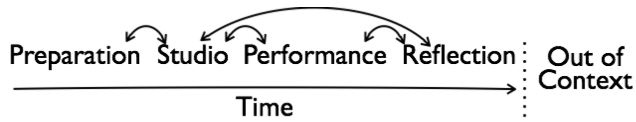


Figure 33: Interview study: Participants' creative phases with possible iteration paths.

a *"wind sequence"* as if being pushed by wind, feelings: P4 choreographs a *"moment of hate"*, to more abstract concepts, such as song titles that remind them of the movements in the choreographic object.

I collected many examples of choreographic objects that constitute the final outcome of the composition process, but that do not represent the concrete sequence of movements in the piece. In fact, two participants (P2 and P6) use a *"constraint-based composition"* approach: They do not formalise movement directly, but instead specify rules that govern it, allowing the performers to create or discover concrete movements by exploring the space defined by these constraints.

CREATIVE PHASES

Participants' creative processes, despite being personal and highly diverse, include a set of phases shown in Fig. 33: *preparation* (before working with the dancers), *studio* (interacting with the dancers and the support materials), *performance* (during the shows), *reflection* (after a studio session or a performance), and *out of context* (stories not related with their current project). Regarding this last phase, for most (5/6) participants it is important to annotate ideas even when they are not directly related to their current project, because they plan to develop them in the future, because they were inspired while doing something else, or because they felt the need to journal their experience.

Given that choreographic composition is an iterative and interactive process, it is not surprising that the very limits between these phases are not always clear. Only two participants spontaneously spoke of well-defined phases; the others articulated them in a more fluid or implicit way. Choreographers might, for example, loop several times over *preparation-studio-reflection* before the *première*, or they may work on different phases in parallel for different parts or aspects of the piece. P1 and P2, for example, both started with a preparation stage that included the search for a movement and sound vocabulary. Interestingly, P2 considers this phase as a *"mental project"*. P1 created the initial structure of the piece, and P2 tested the generated movement material in her own body, transitioning to *"a more corporal project, a stage of verification of the feasibility of the composition"* (P2). They both then passed to

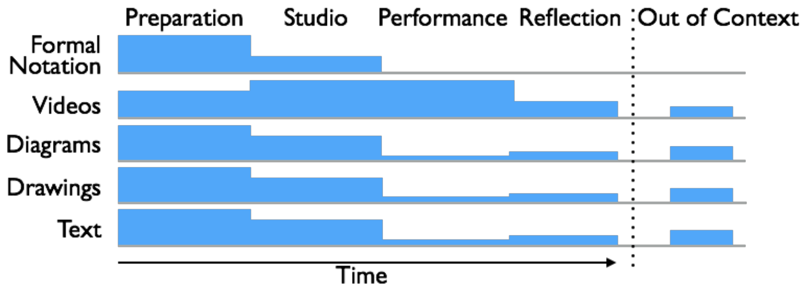


Figure 34: Interview study: General use of representations along the creative phases.

a long studio phase working with the performers, followed by successive reflection phases after rehearsals, including collaboration with an *"external eye"* who would correct details or propose changes. Shortly before the *première*, P1 repeated the whole process *"in a micro scale"*.

This set of creative phases is not exhaustive: It illustrates the commonalities between the study participants' processes, but other specific phases could be present in the workflow of other choreographers. Phases can be repeated, combined, held in parallel, appear in slightly different orders, and be more or less emphasised by each choreographer.

REPRESENTATIONS

All participants represent their choreographic objects with *drawings*, *text*, *diagrams*, and *video*. Half (3/6) of them also use some type of *formal notation*. Fig. 34 shows the general use of these representations along the creative phases. Drawings, text and diagrams are created primarily during the preparation phase, modified extensively during or after rehearsals, and occasionally when an idea occurs outside of the context of the project. They are rarely referred to during the performance or when reflecting upon the piece. For example, P6 started by writing text from inspirational readings in yoga and meditation, making symbolic drawings and referencing books. She kept the mapping between this material and the score only in her memory. For her, the creative decisions to transform the high-level ideas into concrete movement constraints were *"evident"*: *"It's obvious*[1]*, it has to be that, and nothing else"* (P6). P2 made a diagram to represent how sound is transformed in relation to movement (Fig. 35a). She also created schematic collaborative drawings with the composer, during a discussion in which they drew at the same time (Fig. 35b). P1 drew *"rough drafts of human figures"*, with text directions, e. g., *"do it several times"*. He organised the figures in *"vignettes"* in his note-

1 Original in French: *"C'est une évidence"*.

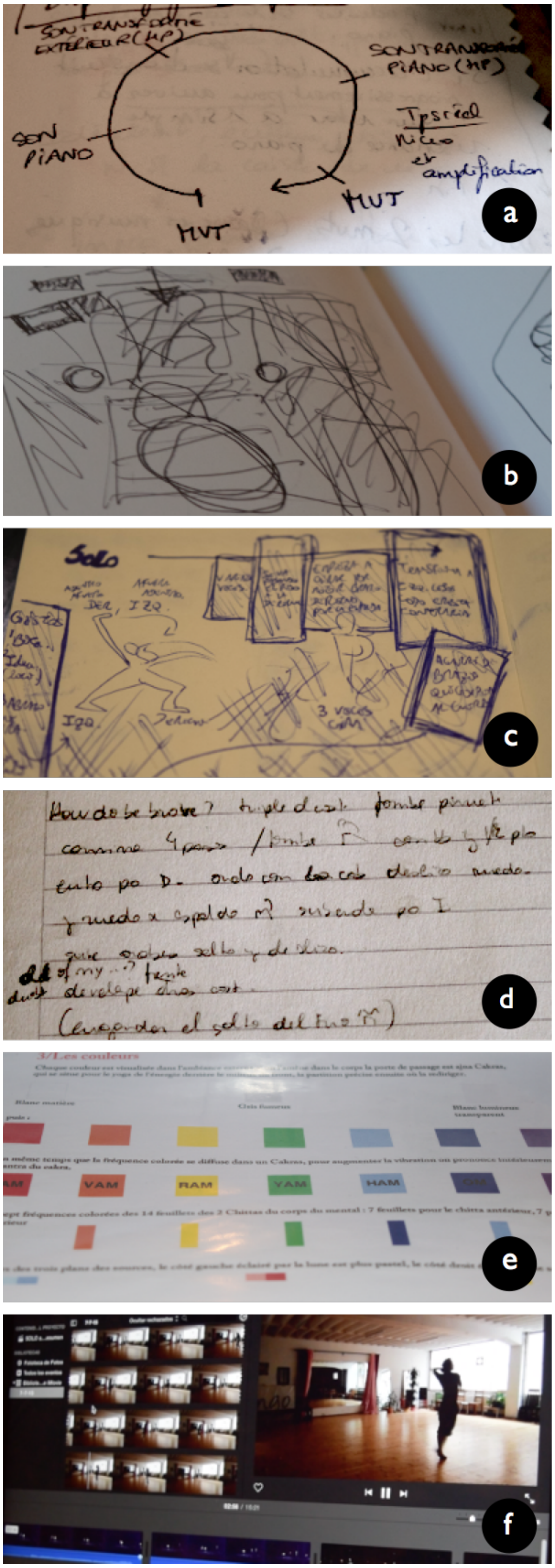


Figure 35: Interview study. Examples of representations: Diagram of sound transformation (Amandine Bajou) (a). Collaborative schematic drawing with composer (Amandine Bajou) (b). *"Vignettes"* of movement in notebook (Matías Tripodi) (c). Very subtle in-line drawings (Fernanda García) (d). Printed diagram of flow of chakras (Myriam Gourfink) (e). Video editing in *iMovie* (Matías Tripodi) (f).

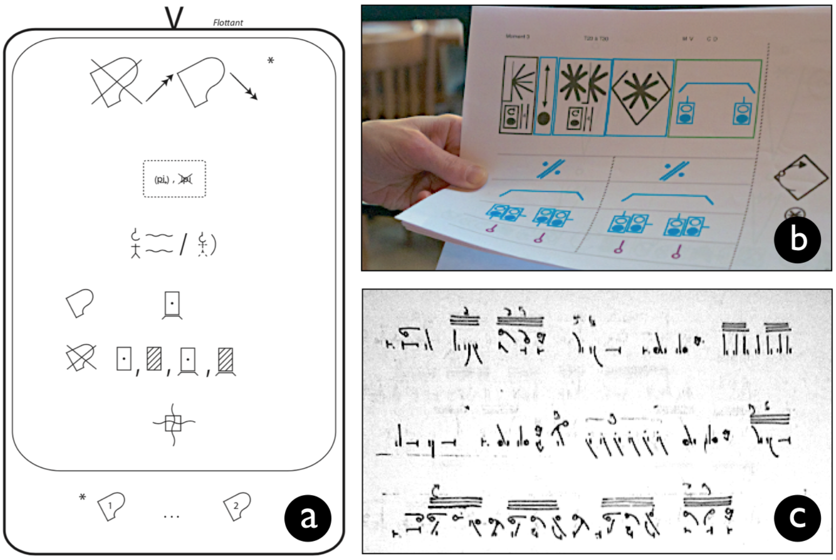


Figure 36: Interview study: Digital score from *"Collision hétérogène"* (Amandine Bajou and Marc Garcia Vitoria) (a). Myriam Gourfink's printed score (b). Matías Tripodi's tango notation (c).

book, using arrows to guide *"the temporal succession"* (Fig. 35c). For P1, these vignettes provide *"a sequence of frames that let me save an idea"*. P3 drew very subtle drawings in line with the text (Fig. 35d). For almost all the examples I collected, drawings were augmented with text, typically to explain what it was not possible for participants to transmit by sketching. Interestingly, for P2, *"we can capture the same things with text and with symbols. Symbols are simply faster and more direct, once you precise how do they work"*.

Half (3/6) the participants write only keywords or very short sentences to record their choreographic objects. Surprisingly, the participants who use formal notation write long texts at the beginning, either to capture inspiration (P1, P6), or to work out ideas and *"avoid including text in the final score"* (P2). These three choreographers also create digital documents to support their creative process. P1 keeps a text file with columns for scenes, lights and transitions. P2 and P6 create digital versions of their scores with graphical editing tools (Fig. 36a and b). P6 also prepares diagrams that represent higher-level ideas, such as the intended flow of dancers' chakras (Fig. 35e). Surprisingly, P6 uses a legacy application which allows her to reuse previous work, but this requires her to keep an outdated computer, with an outdated operating system, in order to run it.

All participants capture video in the studio and during performances; some (2/6) film themselves while exploring movements during preparation. They watch the videos alone or with the dancers as they reflect upon the piece. P4, in addition, shares the

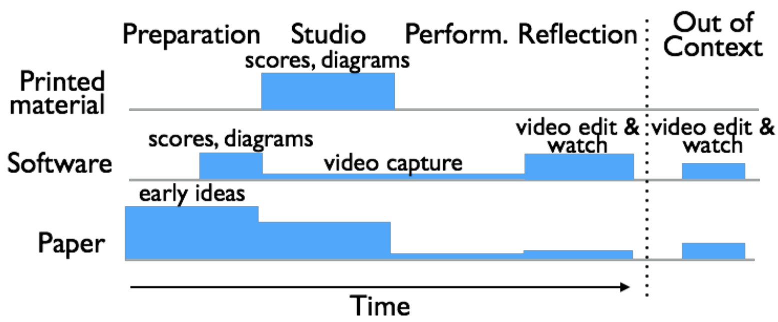


Figure 37: Interview study: Supports generally used for representations along the creative phases.

videos with the dancers within a social network group. P1 films himself performing variations of a movement and then does not watch the videos again, in spite of knowing that he will not remember all the variations. P6 told me a story where she solved a choreographic problem by watching a video from a rehearsal at a slow speed. P6 and P1 edited video with *iMovie* (Fig. 35f). While P6 does so to obtain short fragments that support transmission to dancers, P1 explores movement ideas by playing with video speed, reversal, etc.

None of the participants use a pure formal notation system. P2 and P6 adapted Labanotation for their own needs, augmenting it with symbols they consider more suitable for composition (Fig. 36a and b). P1 developed his own notation for tango choreographies (Fig. 36c). Although these participants do create scores of their pieces, they also craft diagrams or drawings with textual indications to complement them.

All participants use paper to represent their ideas (Fig. 37). P1 told me: *"Through paper I can have a very personal register of the piece"*; P4 recognised: *"I need the paper"*; P2 summarised the creative process as *"a constant back and forth between the paper, the ideas and my body"* (P2). Some participants appropriate their notebooks, for example P5 uses temporal colour codings, and leaves a series of graphical *"traces"* to link pages together. She stated that her notebook is an important object for her and for the dancers.

Most (5/6) participants crossed over elements they were not happy with, that were replaced later. However, when probing for changes, I found several examples of non-recorded decisions that were memorised by the participant, or by the dancers. I also got stories that involve printing a score of the piece, making multiple iterations of handwritten corrections on the printed surface as the rehearsals went by, and only updating the digital version at home, before printing the final score. This illustrates how, from the users' perspective, digital supports are sometimes harder to modify than a non-interactive hard-copy of the documents.

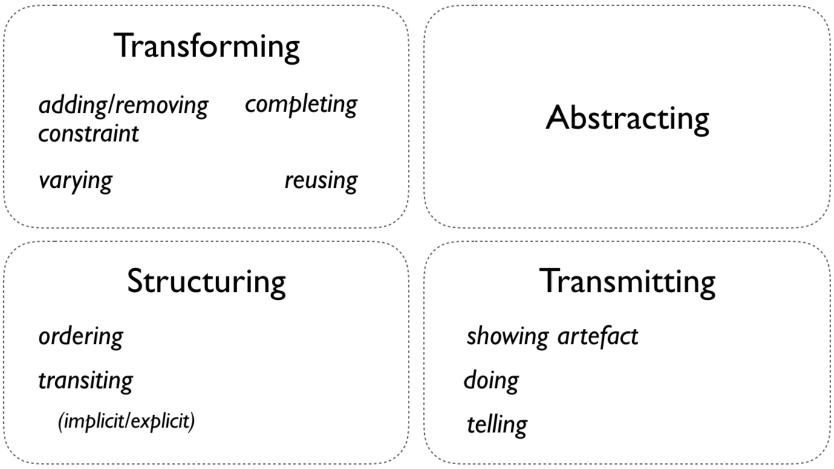


Figure 38: Interview study: Types of operations on choreographic objects.

OPERATIONS

Operations are actions applied to choreographic objects, resulting in new choreographic objects or refined versions of the existing. We identified four categories that are present in at least one story from each participant: *transforming*, *structuring*, *abstracting*, and *transmitting* (Fig. 38). They are key points where the choreographer's skills come into play.

Transforming implies modifying existing choreographic objects, either to make them evolve or to create new ones. P2 told us that she and the composer gave themselves freedom to generate *"a variety of movements, a maximum number of possibilities, to maybe come back to one of the previous"*. Transforming can be achieved by *adding or removing constraints*. For example, P1 told the performer: *"Now do it as if you were in a cold room"* (metaphoric constraint), whereas P6 removed a spatial orientation constraint imposed on the dancers, in order to solve a choreographic problem. This is similar to Onarheim's (2012) observations of designers adding and removing constraints to better define a design problem or to generate new creative directions. Another strategy is *varying choreographic objects* through actions such as changing the body parts involved, mirroring, inverting, or changing the speed. Interestingly, P1 applies all these actions when composing or teaching dance, but he also uses the last three when editing video segments after improvisation sessions. Another method of transforming choreographic objects is to *reuse* them, for example, through repetition. P5 explicitly refers to previous choreographic objects in her compositions: *"Final sequence just like in Intro"*. Participants also transform by *completing* a choreographic object, which entails defining additional aspects or specifying existing details. For example, P1 stated: *"The movement came to me and I drew it, and as I* *practised it, and thought about it, I defined other things to complete it"*. P6 watched videos of the rehearsals with the dancers, in order to fix elements of a sequence that had been *"free"* before.

Structuring refers to combining choreographic objects to give structure to the piece. P1 created a *"draft of movements"*, a list of early ideas without a defined temporal succession, that he later ordered to structure the piece. P6 drew a digital diagram with the *"key situations"*, highlighting the group of dancers' trajectories. P5 defined *"modules"* that the dancers could combine in time under certain rules, resulting in a different structure every performance. The most frequent types of structuring in the stories were *ordering* (putting the choreographic objects in a certain temporal order or defining the rules for dancers to do so) and *transiting*. *Transiting* operations are associated with the way the choreographer conceives transitions between choreographic objects. For some participants, transitions are as important as the choreographic objects, and they spend considerable effort in defining and transmitting them to dancers and other collaborators. P1, for example, keeps a shared digital document (*"the script"*) that contains very detailed transitions. We noticed two main kinds of transiting: *implicit* (the piece is seen as a sequence of choreographic objects in which transitions are indistinguishable; for example, P3 identifies *"moments"* such as *"calm"* and P4 *"states"*, e. g., *"love"*), and *explicit* (the piece is composed of choreographic objects and explicit transitions between them, as in P1's story, where he keeps a list of *"scenes"* and *"transitions"*, specifying how transitions are triggered, what should the dancers do, etc.).

Abstracting a choreographic object represents the act of zooming out from it: displaying less detail to see the big picture, to get a global sense of the choreographic object and its surroundings, to visualise its relationships, transmit it, or analyse it for decision making. This is a fundamental operation that we detected in all participants' creative process multiple times. For example, P2 was speaking to the composer about a choreographic object, when she drew *"only the elements needed to recognise it"*, so that they could refer to the specific object and discuss it. They also created a *"summary of sections"* to *"visualise the piece globally"* (P2). P1 emphasises the importance of specifying *"only a few parameters that describe movement"* for both composing and transmitting choreographic objects. In her notebook, P5 writes with different pen colours *"the big thing"* and *"the details"*. She transmits *"what has to be done: the dancers' coordination'*, leaving *"details such as transitions"* to a later stage in the process. She also uses abstraction by looking at her own shadow on the wall in order to check how a movement looks: *"The mirror gives too much detail I am not interested in seeing"*.

Transmitting a choreographic object to dancers and collaborators is achieved in the collected stories via *showing an artefact* (mostly scores and videos), *doing* (actually performing the movements), *telling* (explaining the choreographic object verbally), or combinations of these strategies. We noticed that participants tend to transmit choreographic objects by showing an artefact or by doing the movements when they already have a defined idea that they want to teach, while they turn to verbal indications when the idea is still vague or open. P1, for example, gave the performer an indication *"that was not enough at all, just a rough draft to test the creativity in the answer"*. We also consider in the transmitting category the examples in which the participants try out a choreographic object with their own bodies, since they are transmitting it from a mental cognitive level to an embodied one, usually with the purpose of making movement decisions. Typically, when applying a transformation, participants assess the results by performing the movements themselves. For example, P4 only keeps a newly generated movement *"if it feels comfortable and organic, if it is real"* in her body. However, some participants (P1 and P2) also transmit the movements to their collaborators, who they call an *"external eye"* that provides feedback.

This set of operations is not exhaustive, and other choreographers might perform operations that do not fit clearly in one of these general four types, but we believe that a great range of operations can be described by combining them.

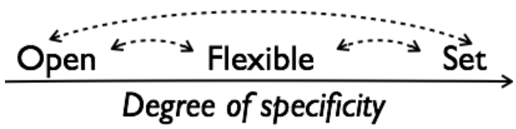


Figure 39: Interview study: Degree of specificity of choreographic objects.

SPECIFICITY

Participants define their choreographic objects with various degrees of specificity. For example, P5 started by writing goals — a list of sensations to convey through the piece — rather than *"pre-designed sequences"*, and P6 collected texts about inspiring topics, and defined the global idea for the piece, without any explicit connection to concrete movements. Most (5/6) participants gave guidelines to dancers to generate movement material. P2 created a score precisely defining aspects such as the body zone involved, the type of movement, the orientation in space, the levels (height of the dancers' bodies with respect to the floor) and how they evolve over time, while leaving the order of the choreographic objects and their concrete trajectories up to the performers' choice.

P3 designed many sequences using a technical vocabulary inspired by ballet, with precise temporal indications.

As we see in these stories, participants constrain certain aspects of their choreographic objects and operations, while leaving others to the dancers' interpretation. In this continuum of specificity (Fig. 39), a choreographic object can be characterised as *open* (e. g., P6's global idea for the piece), *flexible* (e. g., guidelines) or *set* (e. g., P3's concrete sequences). We do not imply that in a set choreographic object every aspect of the movement is completely described, nor that it is predetermined or predictable, given the interpretative nature of some approaches to dance, and bearing in mind the great richness of each individual body's expression and signature.

The degree of specificity changes along the creative phases. Participants typically start by defining their ideas in an open way during preparation, and as they iterate, they increasingly constrain these ideas by operating on them. These results are compatible with Garcia et al.'s (2014) study of contemporary music composers. However, some participants (for example, P6) define some choreographic objects very specifically from the beginning. Participants also leave some choreographic objects open (or flexible) throughout the whole process: open does not mean unfinished, it can be purposely incomplete or abstract. On the other hand, choreographic objects that code rules and constraints instead of movements or gestures, can be precisely set and yet the dancer's movements can actually be more improvised than the resulting from a flexible constraint upon movement. Even though the shift in specificity is typically towards more specific choreographic objects, the other direction can be taken, for example, when solving choreographic problems by removing constraints, or when stepping back to visualise elements from a more abstract perspective. There is a fascinating interplay between the number of constraints applied, the nature of the choreographic object or operation on which they are applied, and how much the resulting movement is fixed.

Representations vary with the degree of specificity. Open choreographic objects are typically described using text and sometimes drawings, set ones seem more compatible with formal notation and video, and flexible ones tend to present a combination. Despite these trends, participants decide when and how to use each representation according to their needs.

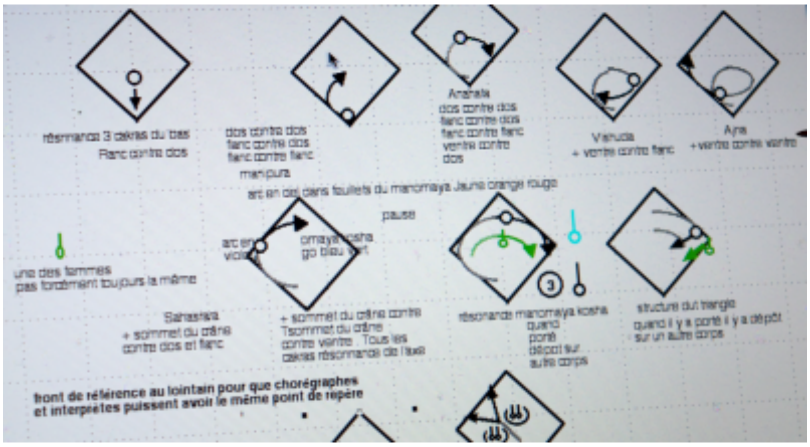


Figure 40: Interview study: Focal point *"stage"*: Floorplan with group of dancers' trajectories (Myriam Gourfink).

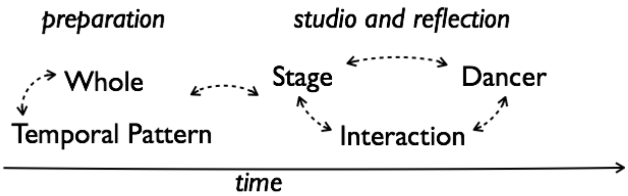


Figure 41: Interview study: Focal points along the creative phases.

FOCAL POINTS

When composing a piece, participants shift between different levels of abstraction — in depth — but also between different *focal points* — in width. Participants define choreographic objects with the attention in the piece as a *whole*, in the *stage*, in a particular *dancer*, in an *interaction* (between dancers, with an object, with the stage, with an idea), and in *temporal patterns*.

For example, P6's scores have *"movement notions"*, since she is *"not interested in describing movement ... [but] in giving the idea for the piece"* (focal point in the *whole*). More than half (4/6) of the participants draw floorplans where each dancer or group of dancers is represented by a circle or a cross, and their trajectories are indicated with lines, as shown in Fig. 40. P1 designed movements based on the constraints of a bandoneon[2] to produce sound (*interaction* with an object), and P4 wrote a sequence that two dancers should perform mirroring each other (*interaction* between dancers). More than half (4/6) of the participants composed at least one sequence for a particular dancer (*dancer*). P2 drew a *"temporal shape"* diagram of the piece in order to agree on the *"global intensity"* with the composer (*temporal pattern*).

Focal points are shifted along the creative phases (Fig. 41). In

2 A musical instrument in the concertina family, very popular in Argentina and Uruguay.

the preparation phase participants usually start defining choreographic objects about the piece as a whole and some global temporal patterns, refined later in the studio by focusing on the stage, interactions, and eventually a particular dancer. However, participants might decide to start from any focal point and switch back and forth in width as the process evolves.

Participants rely on their choreographic skills, intuition and memory to map the elements in different focal points. For example, most (3/4) of participants who draw floorplans keep separate notes about the movements that individual dancers will make to concretise their trajectory, but I have not seen any recorded mapping between these documents.

Different representations appear more suitable for different focal points. For example, drawings of floorplans are used in the stories to represent choreographic objects focused on the stage, text to describe ideas about the piece as a whole (or to complement drawings), videos to capture the interaction between dancers, and formal notation to specify the sequence for one ore more dancers.

6.4 CHOREOGRAPHIC OBJECT–OPERATION FRAMEWORK

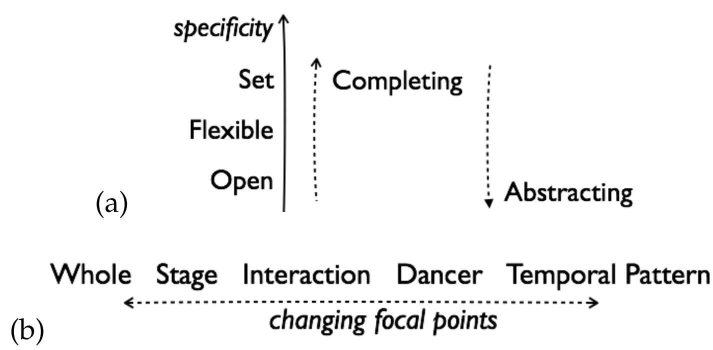


Figure 42: Interview study: Shift in depth (a) and in width (b).

The above six categories form a framework that captures the key elements of participants' choreographic practices. *Choreographic objects* serve as the *focal points*, with a certain degree of *specificity*. They are expressed via different *representations*, and evolve through several *creative phases* as the choreographer applies *operations*. A focal point may refer to the whole piece, the stage, a dancer, an interaction or a temporal pattern, and may be defined in an open, flexible or set way. Choreographic objects can be represented with combinations of drawings, text, diagrams, video, or formal notation, and, for example, be partially created in a preparation phase, then transmitted and transformed multiple times in the studio or in a later stage of reflection.

During the composition process, participants create, edit, and transmit choreographic objects and operations. They constantly shift across levels, both in depth and in width (Fig. 42). They play with the specificity of the choreographic objects (depth) by applying the operations in the categories of abstracting and completing. They also switch the focal points (width). P2, for example, told me she works in several *"strata"* with the music composer, *"going far in each stratum"*.

Participants rely on choreographic artefacts to complement corporal and verbal explanations. Given these findings, we wonder: Why do they record so few changes when they compose a piece? Why does a considerable part of their decision-making process remain implicit? One possible reason is the lack of tools for recording, accessing, and manipulating their material without requiring excessive time or effort. P1 felt that some choreographic problems could benefit from technology, particularly when communicating *"conditions"* and transitions to dancers, and to transmit specific modifications. He also expressed the need to visualise the *"elements"* of a piece and to *"try different orders"*. In addition, all participants had trouble remembering the meaning of certain notes or drawings, stating that during the composition process they remembered instantly. Participants who use some type of formal notation, still prepare diagrams or drawings and textual indications to complement their scores. These findings suggest that current formal notation is not sufficient to fully represent choreographers' ideas, even after they make personal adaptations to the notation system or even create their own from scratch.

6.5 IMPLICATIONS FOR DESIGN

Based on the findings, I identify the following implications for the design of interactive tools to support exploration and documentation of ideas in the choreographic creative process:

Interactivity: Tools should provide interactive ways to visualise and manipulate choreographic ideas and operations that can be shared with dancers and other collaborators. The interviews indicated that while some choreographers resist screen-based interaction, all include paper as an essential part of their creative process. Paper is a flexible, portable support that allows choreographers to rapidly generate diverse representations of their ideas, in a variety of settings. My goal is to augment rather than replace choreographers' existing practices, enabling them to personalise and appropriate the technology to suit their needs. Therefore, tools should keep the flexibility and freedom offered by paper, while adding interactivity. I believe this is key for any tool for choreographers that tries to tackle the early phases of the creative process in terms of exploring and documenting ideas.

Knowledge availability: Tools should leverage the accumulated knowledge about the piece, making previous ideas easy to retrieve. By doing so, tools would be rendering knowledge available for discovery and reuse at multiple levels — choreographic ideas, objects, operations, etc.

Shifting: Tools should track links between the artefacts produced at each level of abstraction or focal point, and support strategies for recording incomplete choreographic ideas and operations. Tools should act not only as an external memory that keeps trace of the decisions and the evolution of the piece, but also as instruments to approach and assess one idea from several perspectives, quickly shifting among them. In this context, choreographers should be able to record their ideas with the desired level of formality.

Distributed cognition: Tools should support choreographic knowledge distribution and collaborative creative decision-making. Choreographic processes are distributed across many elements, such as the choreographers' and the dancers' knowledge, individual and cultural influences, skills, and the environment (Kirsh, 2011a). The findings from the interviews reflect this, especially in the interaction among dancers and choreographers as they explore movement possibilities, collaboratively make decisions, and share their memories of the piece. Tools should recognise this distribution and augment creative collaboration.

Situated action: Tools should take into account the multiple and diverse settings in which choreographers and dancers might use them. Choreography is a key example of situated action (Suchman, 1987): Choreographers may plan a considerable part of a piece during the preparation phase, but the work in the studio necessarily forces them to adapt these plans, refine them in relation with the dancers and the present constraints (stemming from bodies, skills, stage or venue characteristics, etc.), and take alternative paths. Tools for choreographers should be lightweight and mobile, and consider a variety of different scenarios of use. For example, during studio time, users might split their attention between the tool and collaborators, whereas during a reflection phase they may be in a more calm environment such as their home, where they can engage with the tool for longer periods.

6.6 SUMMARY

I conducted critical object interviews with six professional choreographers, who guided me step-by-step in the creative process of a recent piece they choreographed. We identified six categories that capture common patterns in their current practice, and created a framework that articulates them. Based on this framework, I extracted various implications for the design of interactive tools to support choreographers in their work.

Creating a framework for such a dynamic field as dance, which constantly tests and breaks its own habits and rules, is challenging. Contemporary choreographers not only have heterogeneous creative processes that are thus very hard to generalise, but many often work in highly collaborative ways with dancers. There is an inherent beauty and uniqueness in this field that might resist, at a first sight, attempts of characterising or extracting common patterns from it. However, I believe that establishing theoretical frameworks sets the bases to design interactive tools that recognise and preserve the uniqueness of each artist, leveraging higher-level commonalities.

6.7 OBSERVATIONAL STUDY WITH CHOREOGRAPHERS AND DANCERS

The interview study described above gave me insight about the diversity of choreographic ideas and operations that choreographers work with, and the types of representations they use to express them and communicate with their collaborators. Before designing novel tools for choreographers, I wanted to collect more examples about how they record ideas without interactive technology. I decided to concentrate on sketching, notating and annotating, so I ran an observational study with professional choreographers and dancers where they captured their compositions on paper.

Participants: We recruited a France-based professional choreographer with 34 years of experience as the lead choreographer, and four of his regular collaborators, all women, including two choreographers, one dance professor, and one dancer. My thesis advisors and I attended as participant-observers.

Setup: The study was run in the lead choreographer's (LC) usual rehearsal theatre. He had just begun a newly commissioned work, which served as the foundation for the day's activities. We discussed the programme with him, and he was free to propose specific exercises and determine the roles of the other participants. He decided that each dancer would create their own choreographic fragment individually. Together, we chose a set of activities that fit into his established work practice, while also providing data that we could compare across participants.

Procedure: The session lasted approximately four hours, including a working lunch break. The *composition* activity involved *composing* a choreographic fragment. The LC decided when to stop (approximately one hour). Participants captured the dance fragment on paper using A3 paper, coloured pens, highlighters, stickers, and post-it notes. The *transformation* activity involved *transforming* the choreographic fragment (approximately one hour). Participants chose a set of operations to apply to the fragment. We provided possible operations inspired by the framework in Section 6.4, including: *sequence*, *reorder*, *reuse*, *vary speed, rhythm, energy, or spatial patterns*, *define transitions*, *add detail*, and *abstract a choreographic object*, but LC was free to suggest alternatives. When LC asked the dancers to stop, each updated their annotations. Participants were debriefed at the end of the session, and asked for explanations of their annotations from both activities.

Data collection: I recorded video and audio of the session, I took hand-written notes, and photographed participants' artefacts.

Data analysis: I first translated the raw data to English, as most participants spoke French as their first language. I analysed my notes, photographs, videos, and participants' explanations of their annotations to identify which aspects of the choreographic fragments they captured and how they were represented. I looked for both common patterns and unique annotation practices.

6.8 RESULTS AND DISCUSSION

The LC brought images as a creative stimulus and showed participants a set of eight words to inspire sculpture-like body postures, with the constraint of finding linear, fluid transitions between them. He asked each participant to create her own choreographic fragment. During the *composition* activity, each participant performed her choreographic fragment in turn, based on the LC's directions. During the *transformation* activity, the LC asked participants to focus on *repetition* as a key operation for transforming their fragments. One participant joined the session late, when the others were about to annotate their fragments, so she captured hers without dancing it first. The LC remarked that writing the movement had an impact in the way she moved, *"especially in the use of space and orientations"*. Interestingly, the LC only took notes on his personal notebook while the participants were performing, but did not record the whole fragments.

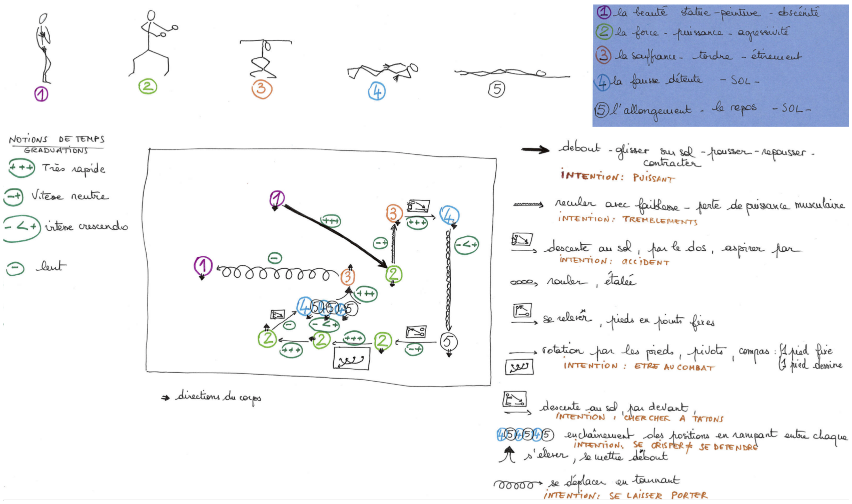


Figure 43: Observational study: Choreographic fragment captured on paper (P3).

choreographic objects

As in the previous study, we found that all participants represent their choreographic ideas by defining *choreographic objects* at different levels of abstraction and detail, which they illustrate with a combination of sketches, text, symbols, and diagrams. For example, some participants drew floorplans (diagrams that represent spatial trajectories, as seen from above), focusing on the displacement of the body with respect to the stage. They also sketched different body postures, which let them focus on the details of a particular moment of the fragment (Fig. 43).

Although LC defined the higher-level choreographic object (the eight sculpture-like postures) the participants all composed their own individual variations, at diverse levels of detail. Their sketches each contained different subsets of choreographic elements. For example, only P2 (dancer) represented movement duration in her floorplan, and only P4 (choreographer and dancer) considered music and lights.

personal sublanguages

One participant (P1, dance professor and dancer) already had her own personal sublanguage, which she used to represent movement, including spins and shifts in weight or direction (Fig. 44). The other participants created their own ad-hoc sublanguages during the activity. All four participants created legends to explain their symbols (Fig. 45 shows an example).

Figure 45: Observational study: Legend in P1's fragment.

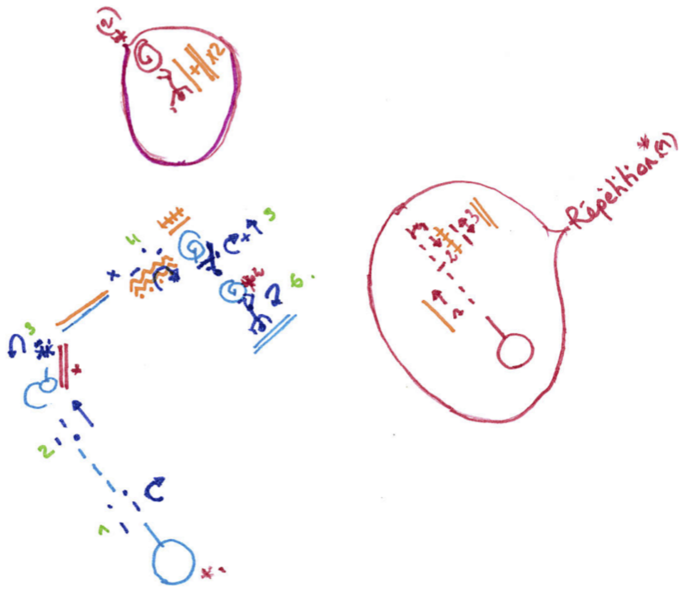


Figure 44: Observational study: P1's fragment with her personal sublanguage.

DIFFERENT REPRESENTATIONS OF CHOREOGRAPHIC OBJECTS

All participants annotated movement qualities, i. e. the qualitative attributes and characteristics of movement (Blom and Chaplin, 1988). For example, P1 and P2 mapped symbols to personally meaningful words: P1 described movements as *"tight - contracted"* whereas P2 used *"uneven"* or *"dented"*. Most participants (3/4) annotated *"movement intentions"*, with differing levels of detail and type of representation (symbols and words). All recorded transition speeds, but in idiosyncratic ways. For example, P4 used words related to speed (e. g. *"very fast"*); others assigned specific symbols. All but one participant (3/4) specified levels, and used symbols, text or both to specify rotation, body orientation, or gaze direction.

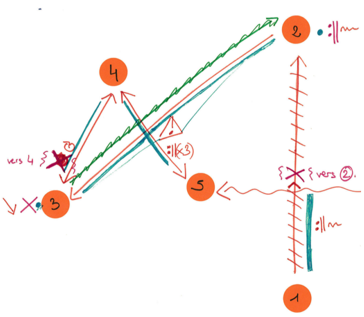


Figure 46: Observational study: P2's transition lines do not represent concrete spatial trajectories, but their duration.

All participants created floorplan diagrams for the sculpture-like postures, with transitions among them. Each participant created different line styles to represent transition types. For example, P3 (choreographer and dancer) added complex symbols representing qualities and intentions for each transition (Fig. 43).

Interestingly, although P2 drew lines to show transitions (Fig. 46), she said that their trajectories were *"free"*, and constrained instead the movement qualities and *"moments of transformation"*. Her lines indicated movement duration, rather than a concrete spatial trajectory. Diverse techniques for representing postures in floorplans included: numbers (P1, P3), coloured-dot stickers (P2), and crosses (P4). Participants also found diverse ways to draw and annotate postures: P2 specified body part positions with symbols indicating the main movement quality, P3 wrote keywords, and P4 sketched minimalist postures inline with text descriptions (Fig. 47).

Participants often created multiple representations of the same choreographic object. P1's posture sketches included a symbol for the main quality, with arrows to indicate gaze direction and the intended movement of each arm and foot (Fig. 48). Yet her diagram (Fig. 44) marked only arm and foot positions, or sometimes a single arm for a particular posture, because she wanted to emphasise that *"it was extended"*. She produced multiple views of the same object, from different perspectives (above versus front), and at different levels of detail (position of the whole body versus arms and feet).

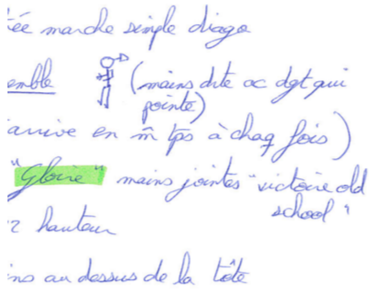


Figure 47: Observational study: P4's minimalist posture sketches inline with text descriptions.

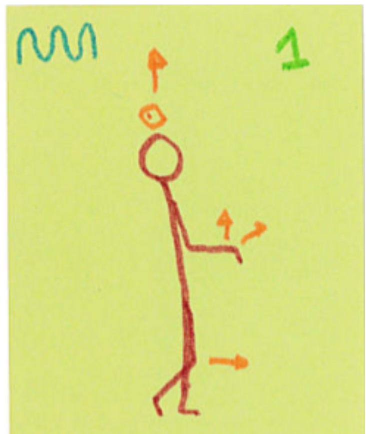


Figure 48: Observational study: P1's posture sketch with symbols for movement quality, gaze direction, and limb movements.

RULES BEHIND THE MOVEMENT

Most participants annotated the rules that constrain and describe the movement in their fragments, rather than the movement itself. In fact, P2 referred to her legend as a *"panel of possibilities"* from which *"it is possible to choose"*.

6.9 SUMMARY

We observed considerable variability in how participants represent choreographic objects and operations, even given the same initial constraints (eight words to inspire eight postures, with linear transitions between them). Participants also varied greatly in their choice of which aspects to capture for each fragment. Even so, several common features emerged: All participants specified movement speed and movement qualities; all drew spatial diagrams (floorplans); and all sketched rules and constraints regarding movement, using a combination of sketches, personal sublanguages, diagrams, and text.

6.10 SUMMARY AND CONTRIBUTIONS

In this chapter, I interviewed choreographers about how they capture and manage ideas when creating a piece, with an emphasis in the artefacts that they produce. Within the great diversity of approaches to dance and choreographic practices, we synthesised the higher-level commonalities into the *Choreographic Object-Operation* theoretical framework: *Choreographic objects* are expressed with a certain degree of *specificity* through different *representations* — typically combinations of drawings, text, diagrams, video, or formal notation. They evolve through several *creative phases* as the choreographer applies *operations* to them, shifting among *focal points* such as the whole piece, the stage, a dancer, an interaction or a temporal pattern.

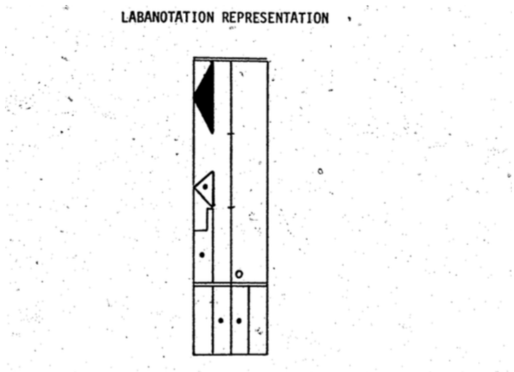
Then I derived a set of implications for the design of digital tools for choreographers to explore and document ideas: Tools should make the knowledge about the piece available, enable shifting across levels of specificity and focal points, and support both situated action and distributed cognition. I used the operations in the framework to spark choreographic activities in an observational study with professional choreographers and dancers, examining how they capture choreographic fragments without digital technology support. From this second study, we identified the need of expressing both the content (movement) and the constraints (spatial and temporal) in personal ways.

7 SUPPORTING THE CREATIVE PROCESS

This chapter focuses on allowing contemporary choreographers to define and manipulate spatial and temporal constraints, in the context of exploring and documenting choreographic ideas. After presenting previous work on this area, I introduce Knotation*, designed based on the findings from Chapter 6 and refined through the input from choreographers and dancers.* Knotation *is a pen-based mobile tool that lets choreographers sketch choreographic ideas and make them interactive. I present the tool in use, through a technology probe study and a structured observation of contemporary choreographers. Finally, I discuss how the design principles behind* Knotation *support users in composing time and space.*

The findings from Chapter 6 suggest that choreographers want to express choreographic concepts in terms of both space and time, and to represent movement in terms of constraints, through combinations of drawings, text and numbers. For this reason, I argue that digital tools to explore and document choreographic ideas from the early phrases of the creative process should support free sketching and multiple representations and views of choreographic objects. This should be integrated with images and video, as dancers have successfully used them to learn and memorise choreographic sequences, and choreographers to revise generated material (Singh et al., 2011; Stevens et al., 2003).

Choreographers should be able to draw the overall structure of a piece, and transition easily between abstraction and detail. They should be able to modify the meaning of particular choreographic objects, delay decisions, and freely explore different combinations. This resonates with Dalsgaard's *transinstrumentality* concept, in which *"competent designers start working with well-known instruments without knowing exactly where they are going and what they want to achieve, and yet as the interaction between designer, instrument and situation unfolds, they end up producing something meaningful, which advances the design process"* (Dalsgaard, 2017). Similarly, rather than forcing choreographers to follow a particular approach or interrupting their creative flow, my goal is to help them create and interact with their own representations of ideas, and in particular, with their own creative constraints.



INPUT INTO LABAN PROGRAM

Type of Movement	Starting Time	Bodypart	Duration	Direction/ Level
2	0.00	ANR	4.00	-
2	0.00	ANL	1.00	-
1	1.00	WLL	1.00	F
1	2.00	WLL	.50	LSM
1	3.00	WLL	1.00	LSL
0	4.00	-	-	-

Figure 49: Input to Wolofsky's Laban program. Source: Wolofsky (1974).

7.1 CONTEXT

Before introducing *Knotation*, I review the literature on the preservation of choreographic material, as well as technology to support augmented sketching and note-taking in domains outside of dance, and annotation and sketching of choreographic artefacts.

PRESERVING CHOREOGRAPHIC MATERIAL

A major challenge in choreography is how to capture a finished work, so it can be archived and performed even after the original choreographer is gone. Formal dance notation systems are cumbersome and heavy to deploy. For example, one Labanotation score can take more than a year to create, not including revisions (Parrish, 2007). This type of effort often requires hiring a full-time specialist, which independent artists or small dance companies cannot afford.

An early attempt to facilitate dance notation through technology was Eshkol et al.'s (1970) computer program to interpret scores written in the Eshkol-Watchmann notation. The program would compute and execute the movement trajectories in the score, displaying them in numeric or graphic form. Zella Wolofsky's (1974) goal was to archive a Labanotation score while preserving *"the feel"* of the dance. Wolofsky implemented a system that interpreted Labanotation commands (Fig. 49) to produce stick-figure graphics of the corresponding movements. As in

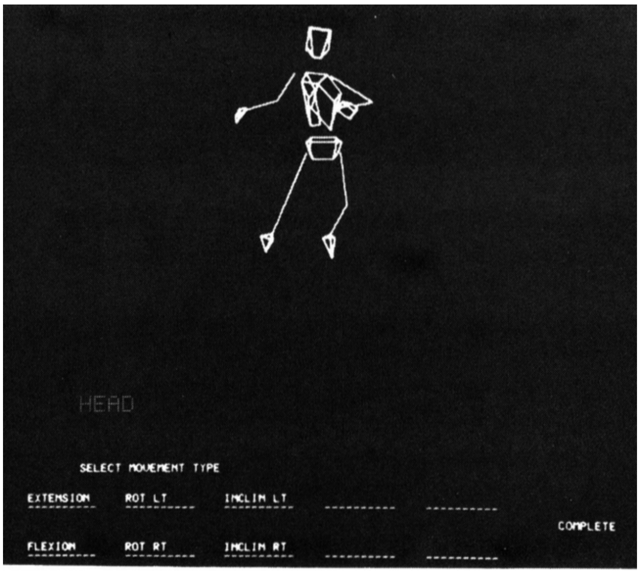


Figure 50: Choosing a body part in the *CHOREO* system. Source: Savage and Officer (1977).

Noll's system (1967), the graphics would be then photographed one after the other, to give the illusion of movement[1]. *CHOREO* was an interactive system built by Savage and Officer (1977) to notate a dance piece and visualise the score as movement. It allowed the user to choose body parts from a menu, as well as the type and degree of movement, in order to animate stick-figures performing the dance sequences (Fig. 50).

Several software applications help speeding up the score writing. For example, *LabanWriter*[2], developed by Lucy Venable and colleagues from Ohio State University, supports the creation and edition of Labanotation scores. A similar system, *MacBenesh*, was built for Benesh notation (Ryman and Hughes-Ryman, 1986). *LabanDancer* translates scores between *LifeForms* and *LabanWriter*, to animate the content of a score while following its notation (Wilke et al., 2005). *KineScribe*[3] is a more recent iPad app that adapts *LabanWriter* to touch-screens (Fig. 51) and has been used in Reed College to foster dance literacy.

However, both Eshkol-Watchmann and Labanotation still require significant expertise, time, and do not capture intermediate artefacts in the choreographic creative process, for example, those documenting the rules and constraints that guide movement generation. In addition, notation methods sometimes leave certain choreographic aspects implicit, thus notators and dancers must deduce the movements based on context and their knowledge of

1 Other works inspired by Wolofksy's are reviewed in Lansdown (1978).
2 Available for download at: https://dance.osu.edu/research/dnb/laban-writer
3 Website: https://www.reed.edu/kinescribe/index.html

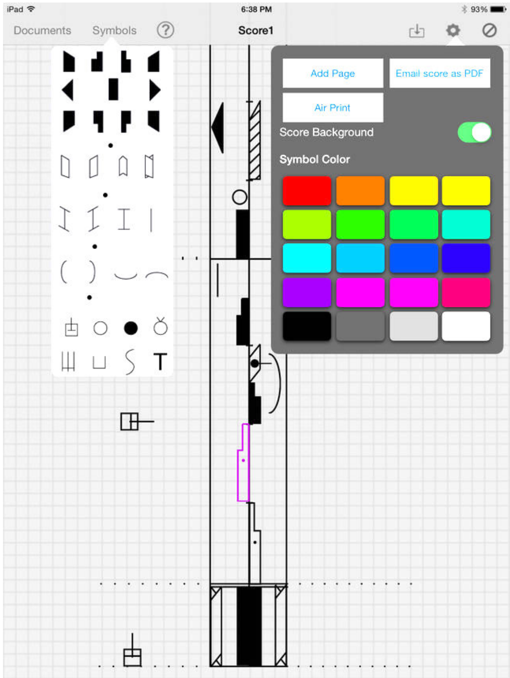


Figure 51: Kinescribe interface. Source: Kinescribe app's screenshot, Apple iTunes.

the piece. For this reason, Calvert et al. (2005) suggested that systems to support score writing should also aid interpretation. As far as we know, none of the systems mentioned above provide this help.

Multiple initiatives have been launched to preserve contemporary choreographic knowledge, including online projects such as *IMK*[4], the *Dance Notation Bureau*[5], and Siobhan Davies Dance's *Replay Archive*[6]. Most projects focus specifically on the work of one recognised choreographer or dance company. For example, Emio Greco|PC's DVD *Capturing Intention* documents choreographic material from the company's *Double Skin/Double Mind* workshop, using descriptions, Laban and Benesh notations, demonstrative video clips, and sound material (deLahunta, 2007). Ribeiro et al. (2017) used 3D data capture to document choreographer João Fiadeiro's choreography, and to produce visualisations of his creative process.

Other projects focused on documenting choreographic processes and methods. For example, in the 1990s, choreographer William Forsythe worked on a multimedia dancer training program to teach his improvisation principles: He was filmed performing examples in over 100 video segments, which were then augmented with animations that traced his paths and revealed

4 Website: insidemovementknowledge.net
5 Website: http://www.dancenotation.org/
6 Website: https://www.siobhandaviesreplay.com/

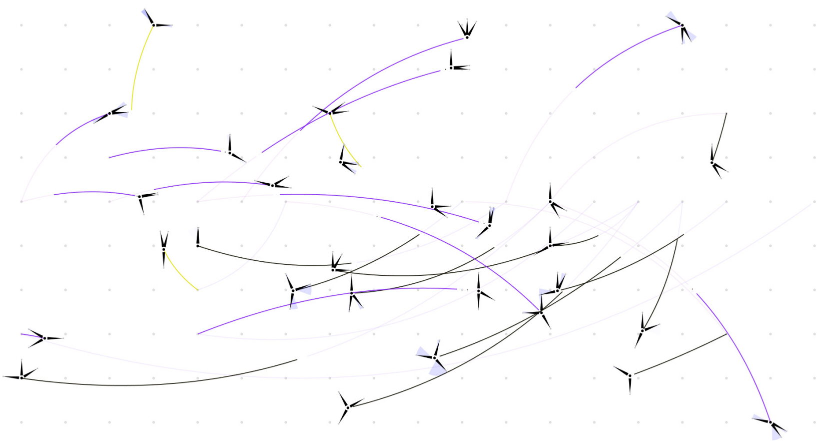


Figure 52: Counterpoint tool in *Synchronous Objects* website. The user can organise the clock-like shapes in and out of unison through slides that control their shape, speed and motion. Source: https://synchronousobjects.osu.edu/media/downloads/Obj6_CounterpointTool.jpg.

spatial relationships around his body (Groves et al., 2007). The prototype, originally designed for use in rehearsals, was refined and released into a DVD called *Improvisation Technologies* (Forsythe, 2012). The DVD included visualisations of his vocabulary and material, and had the goal of documenting and reflecting on choreographic structures, such as alignment and cues between dancers. It became a tool for choreographers and dancers to improve their dance observation abilities. It also created a readable graphical language that served as a bridge to dance for architects and researchers in other fields seeking for ideas on space, structure, and movement (Groves et al., 2007). In this sense, the DVD could be considered the first boundary object produced by the dance field (Groves et al., 2007).

Forsythe's *Motion Bank*[7], an educational multimedia project, continued this initiative by focusing on the creation and organisation of movement in time to produce attractive choreographic pieces. Motion Bank provides a video-based choreographic score and an online interdisciplinary learning environment for the piece *One flat thing, reproduced*, in the context of the *Synchronous Objects* project (Palazzi and Shaw, 2009). The project includes interactive visualisations and tools that play with specific choreographic elements, such as counterpoint (Fig. 52), to inspire choreographers in the generation of new material. The Davies Dance's *Jerwood Bank Project* has been exploring the choreographic processes behind specific pieces of the company, with the goal of transmitting them to younger dancers (Whatley, 2008). Dancers were guided each

7 Website: www.motionbank.org

year through the creative processes used to develop one piece, instead of just learning the finished work. In the 2006 edition, deLahunta and Lieberman brought their digital choreographic sketchbook *Rotosketch*, so that the dancers and choreographers could document the process through annotated video (Whatley, 2008).

These initiatives focus on documenting the final outcome of a particular choreographer's work, or the idiosyncratic nature of a choreographer's or a company's creative process. I seek a more general approach that supports diverse choreographers, with diverse approaches, during both exploration and documentation of creative ideas and processes.

SUPPORTING SKETCHING AND NOTE-TAKING

Among the extensive research in augmented sketching and note-taking, I review tools that let users add personal meaning to their sketches and notes. I focus on those that render sketches interactive, either through explicit actions done by the user or by recognising objects from the user's strokes.

Some tools help designers specify and refine their design ideas. *SILK* (Landay and Myers, 2001) allows designers to sketch user interface elements with a pen or a mouse. For example, the user can draw a scroll bar and then interact with it. Similarly, *DENIM* (Lin et al., 2000) is a pen-based system that supports early-stage web design. Web designers can sketch different interface components and transform them into working prototypes. *DEMAIS* (Bailey et al., 2001) is a pen-based desktop tool that lets designers sketch interactive behaviour and generate interactive storyboards, which they can edit with a dedicated visual language. Gross and Do's (1996) pen-based system captures the vagueness and intended ambiguity in diagrams, in the context of creative design.

Moran et al.'s (1997) pen-based techniques and Mynatt et al.'s *Flatland* (1999) are among the earliest attempts to augment whiteboards, allowing office workers to organise notes and other information during meetings. *Livenotes* (Kam et al., 2005) offers collaborative augmented note-taking for the classroom. A more recent example, *InkAnchor* (Ren et al., 2014), is a pen-based tool for informal note-taking with a mobile device. *InkSeine* (Hinckley et al., 2007) explores a pen-based approach for active note-taking, supporting searching and the incorporation of multimedia files. It provides ways to link annotations to virtual objects and interact with them in context.

I am particularly inspired by projects designed to support artistic practices such as contemporary music composition. For example, both *Musink* (Tsandilas et al., 2009) and *Paper Composer*

(Garcia et al., 2012) let composers explore their ideas on interactive paper, using Anoto technology[8]: They can create personal musical symbols, notations and structures and link them directly to music composition software. *Knotty Gestures* (Tsandilas and Mackay, 2010) offers a minimalist technique for adding mathematical functions, audio and video recordings as well as other features to hand-drawn notes and sketches. Users simply draw a tiny circle or *knot* on any line, and select the desired function from a menu on an Anoto Livescribe pen (Fig. 53).

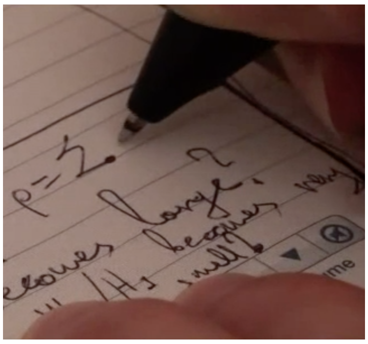


Figure 53: User drawing a *knot*. Source: https://hci-museum.lri.fr/knotty-gestures

All these tools, designed for other audiences and contexts, offer interesting possibilities but none is fully applicable to choreographic practice, which must capture movements of one or more dancers as they move through space over time, according to the underlying principles specified by the choreographer.

ANNOTATING CHOREOGRAPHIC ARTEFACTS

Many choreographers rely on a combination of paper sketches and video to capture their choreographic decisions. Several research projects addressed the annotation of these choreographic artefacts in the context of contemporary dance. *Rotosketch*[9] was a prototype designed to allow dancers and choreographers to sketch over video on a tablet computer, with the goal of exploring links between the action and time of the drawing and the trace that it leaves, in relation with movement (deLahunta and Zuniga Shaw, 2006). The *Creation-Tool* (Cabral et al., 2011) also runs on a tablet and is intended for use during rehearsals. The choreographer can record video of dance sequences, and annotate them with voice and hand-written notes. The *Choreographer's Notebook* (Singh et al., 2011) offers similar functionality with a collaborative web-based tool (Fig. 54). Choreographers and dancers can annotate video outside of rehearsals, which lets them conserve scarce resources. They can also document their choreographic process and revisit earlier choreographic choices. In a more targeted initiative, the goal of the annotation software developed by the *Transmedia Knowledge Base* project with choreographer Rui Horta, is to assist the choreographer's creative process (Fernandes and Jürgens, 2013). *Rekall* (Bardiot, 2015) is an online platform for the performing arts, where users can gather a variety of artefacts about a production (e.g., video, pictures, audio), organise it, annotate it, and compare it with other productions. This not only allows artists to preserve their work, but also enables researchers to identify patterns across multiple productions. Along

8 The Anoto pen's camera captures gestures on paper printed with a computer-readable, human-invisible dot pattern (www.anoto.com).
9 It has not been published academically but an illustration of its use can be found in: https://vimeo.com/16788192

Figure 54: The *Choreographer's Notebook* interface. Source: Singh et al. (2011).

the same lines, the *Motion Bank* project created the web-based application *PieceMaker2Go*[10], a collaborative textual annotation tool for choreographers and dancers.

More recently, Ribeiro et al. (2018) developed the *Virtual Reality Annotator*, a tool for annotating dancers' skeletons or point-cloud data in a virtual reality environment through sketches, speech-to-text, and highlighting. In spite of requiring the interaction with a wireless mouse and an Oculus Rift V2 to manipulate the 3D objects, the authors argued that virtual reality technologies are already *"usable in a dance context with minimal disruption to its traditional practice"*. However, investigations with more choreographers and dancers are required to sustain such a claim, and to determine, e. g., for how long could users engage with the system before feeling tired, how it affects collaboration, how easy it is to retrieve and edit past annotations, etc.

Although each of these systems lets choreographers and dancers annotate their videos (or 3D scenes), none offers them a higher level representation of the choreographic ideas they develop for each piece. I seek to support more general types of annotation and sketches that can be created independently from existing video footage. I do not assume the existence of digital documents about the dance: I want to let users start from scratch, sketching and writing their ideas, and incorporating multimedia at any point of the process if they wish so.

10 The current (second) version can be found in: `http://motionbank.org/en/event/pm2go-easy-use-video-annotation-tool.html`. A third version is still in development.

SKETCHING CHOREOGRAPHIC ARTEFACTS

deLahunta et al. (2004) talked about how contemporary choreographers and dancers use *"the page"* as an interactive object for reflection, collaborative documenting and sharing of ideas. They argued that unlike formal notation systems, drawing serves choreographers' and dancers' needs in leaving *"marks"* that act as traces and triggers to stimulate creativity. To my knowledge, no digital tool supports contemporary choreographers in this type of task beyond annotations coupled with video footage.

Moghaddam et al. (2014) developed a system for ballet choreographers to prototype dance movements. The choreographer can storyboard a dance sequence by drawing stick-figure sketches of a dancer using a set of annotations proposed by the authors (Fig. 55). The choreographer can also trace the path of the dancer, with the mouse or a pen. The annotations are used to retrieve and compose 3D *"mini-motions"* that the authors derived from a database of motion-captured ballet movements. The tool matches the sketched input with the existing mini-motions in order to animate the dance. The choreographer can reorder the sequence of mini-motions to explore different combinations. However, it is not clear if and how the tool would work for several dancers, or very long sequences. Choreographers are limited by the vocabularies imposed by the annotations and the mini-motions database. The methodology does not seem to be user-centred, as the authors only had *"informal discussions with a few ballet masters, choreographers and university instructors"*, and no tool evaluation is offered in the article.

Figure 55: Ballet annotation of a *jeté en tournant* in Moghaddam et al.'s system. Source: Moghaddam et al. (2014).

With a similar but more sophisticated approach, James et al. (2014) proposed a system for synthesising a choreography based on existing dance footage, and a storyboard of stick-figures and action labels that augment them. The user draws the stick-figures in a web-based interface and can manipulate the articulated skeletons. The system matches the sketches with existing poses in a database of archival dance footage, and retrieves the candidates for the user to choose among (Fig. 56). The user can also specify multiple actions (e. g., run, turn), between two poses. Then, the system generates a continuous video based on the selected fragments of existing footage, by identifying and making use of transition frames in it. The authors evaluated the system quantitatively and qualitatively with both low and high definition footage, and found that the similarity between the training and the test footages is more important than the resolution quality. This system is highly valuable, but its potential for generating novel choreography depends on the availability and versatility of footage from pre-existing choreography, and users' sketches are used merely as inputs for the retrieval algorithm.

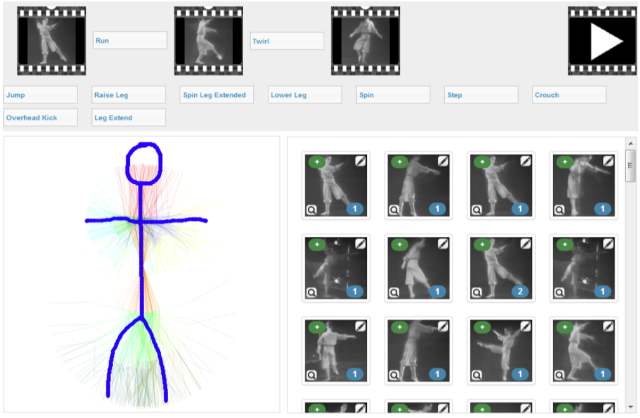


Figure 56: Sketched skeleton and retrieved poses in the *ReEnact* project. Source: James et al., 2014.

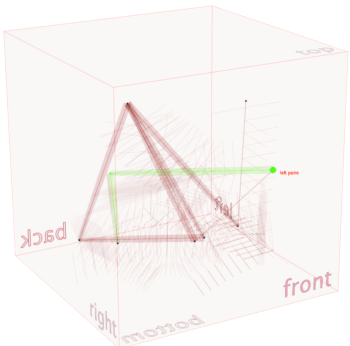


Figure 57: Sketch in the *CLA*. Source: Church et al., 2012.

Church et al. (2012) created the *Choreographic Language Agent* (CLA), a visual programming environment that encourages choreographers and dancers to explore alternative mappings between geometric visualisations and movement in the studio. Instead of prompting dancers with specific movement directions, dancers must solve choreographic problems by creating new movements. The sketches (Fig. 57) are three-dimensional, animated, and can be edited and version controlled. A challenge for the designers was to define a level of formality that let the system process the sketches, while allowing users to interpret them in several ways (Church and Blackwell, 2011). deLahunta (2015) noted that the *CLA* distributes the choreographic problem-solving between bodies and the computer. Interestingly, he described the *CLA* as *"a page"* for working with choreographic ideas interactively, where dancers can manipulate structural relationships that are both *"syntactic or language-like and visual-spatial"*. deLahunta pointed out that the system documents part of the decision-making process and makes it available for later reflection. This tool is indeed inspiring, but the vocabulary is purposely limited to geometric visualisations and transformations, and it does not augment free-hand, personal sketching.

In summary, although many systems attempt to address the choreographic practice, choreographers still lack access to advanced, general-purpose software tools that support the early phase of the creative process, before ideas have been fully developed. My goal is to provide an open-ended, easy-to-use system that supports the early phases of choreographic exploration and documentation, with an emphasis on defining and manipulating creative constraints during the process.

7.2 KNOTATION

In this section I introduce the current design of *Knotation*, initially based on the results from the studies in Chapter 6, and iterated through two user studies that I describe later in the present chapter.

The design of *Knotation* builds on the minimalist approach of *Knotty Gestures* (Tsandilas and Mackay, 2010) to add interactive functionality to choreographers' sketches. However, instead of interactive paper, *Knotation* runs on Apple's iPad Pro™, which can be easily brought into the dance studio. Choreographers can sketch, link and interact with their own choreographic structures and notations with the Apple Pencil™. They can incorporate pictures and video, capturing them *in situ* or using pre-recorded material. *Knotation* provides a history of versions to let users revert to previous states of the document. To facilitate collaboration across iPads, it includes a feature to import the content of another *Knotation*'s document into the current canvas.

The choreographic creative process spans over weeks or months, and often involves close collaboration between choreographers and dancers who try and discard a large number of ideas. The following scenario illustrates how *Knotation* might be used in the early stages of this long, complex process.

USE SCENARIO

Ella is a contemporary choreographer. She is at the beginning of a new project: a contemporary piece for eight dancers that will premiere in six months. Since studio time is expensive, Ella is going to work on some ideas at home before joining the dancers. In her iPad, she browses some inspiring images she has been collecting over the last weeks related to the *hopscotch* children's game, including text fragments from Julio Cortázar's novel[11]. Ella opens *Knotation* and with the pen she writes some words that will guide the creation: *hopscotch*, *earth*, and *sky*. Below the first word, she holds the pen against the screen, and a small blue dot appears: a *knot*. She taps on the knot to reveal the available functions and she chooses *media*. This opens the iPad's photo library, from which she chooses a picture of a hopscotch. The picture is displayed below the knot. She does the same for the other two words. Then she also imports some of the text fragments, writes some more ideas about the piece next to them, and saves the document.

The next day, Ella goes to the studio and introduces the project to the dancers. She shows them her notes in *Knotation*, and as

11 Cortázar, J. (1966). Hopscotch. Translated by Gregory Rabassa. *New York: Pantheon.*

they discuss, the dancers contribute with more concrete ideas, for example: interacting with an imaginary little rock; finding many different ways to move with only one leg on the ground; questioning the order of transitioning among the earth, the path, and the sky. She quickly writes these ideas in *Knotation* as the dancers start moving to explore movements based on them. Ella then observes the dancers and gives them feedback.

While commuting home, Ella decides to record a summary of the day's progress. Since she wants to detail the work regarding each of the three main concepts, she creates a knot over the word *hopscotch*, taps it, and chooses the *portal* option from the menu. The knot turns green and when she taps it, this portal takes her to a new blank canvas. She writes and sketches the key new ideas sparked during the day. She goes back to the main page and repeats the process for the other two concepts.

As the rehearsals go by, Ella and the dancers fix some of the movements, and film each with the iPad. The chosen set does not have an order, and they do not know yet who will perform each or how many times. Before making these decisions, Ella wants to capture and explore the trajectories that these movements imply when performed on stage. In *Knotation*, she enters to the *earth* portal, and starts drawing the trajectories. She decides that a vertical line represents a dancer coming towards the audience, a line to the right means that a dancer goes to the right, a loop represents a turn, and so on. Once she is finished, Ella wants to visualise how everything would look together, so she will turn her sketch into an interactive *floorplan*. She draws the stage around the trajectories and creates a knot over this line. She chooses the *floorplan* type, and everything inside this border becomes orange, meaning that *Knotation* interprets the lines as spatial trajectories. She taps the floorplan knot to play it: The trajectories are animated simultaneously. Ella wants to play with the speed of the trajectories, so she creates a knot, adds an *attribute* to it, specifically, *speed*, and adjusts its value on a slider. Now Ella wants to visualise the movements performed one after the other instead. On the floorplan's border, she creates a new knot and from the available *relationships*, she chooses *order*. The *order* knot has now two values to choose from: *sequential* and *simultaneous*. She chooses *sequential* and this triggers the animation of the trajectories in the order in which they were drawn. Ella notices that the trajectory representing a dancer going to catch the little rock should be performed slower than the rest, so she will set a new constraint. She creates a knot on top of that trajectory and adds a *speed* attribute to it. As she decreases the value, *Knotation* triggers the animation, and Ella stops when she finds the proper speed with respect to the rest.

The next rehearsal, Ella shows the floorplan on *Knotation* to the dancers, so they get a feeling of how fast they need to be relative to the others. A dancer suggests that it would be easier if they knew how long should each movement take, so Ella creates a knot on the floorplan's border, adds a *duration* attribute, and sets its value to 4. *Knotation* animates the trajectories at different speeds so that each takes 4 seconds (except the trajectory that has its own speed knot). The dancers get a better feeling of the whole sequence and start rehearsing it.

At the end of the rehearsal, Ella wants to play with the order and repetitions of the movements. Below the floorplan, she draws a line. Then she creates a knot over it, defines it as a *timeline*, and the line becomes violet. She imports the movement clips via *media* knots, which she places on the timeline. Ella then taps on the timeline knot, and the videos are played from left to right — the direction in which she drew the timeline. Ella reorganises the movement sequence by moving the knots on the timeline. She detects a nice triangular pattern that forms when three movements are consecutive. She wants to highlight this pattern by repeating it at the end of the sequence, so she holds the pen over one of the three knots, and an *edit* menu appears. She chooses the *clone* option and a duplicate of the knot appears next to the original. Ella clones the other two knots, and positions the three at the end of the timeline. In the floorplan, she taps on each of the corresponding trajectories and clones them. She positions the cloned trajectories on one corner of the stage forming a triangle, and plays the whole floorplan to see how it would look. The next day, she proposes this new idea to the dancers by showing them the floorplan and the timeline. Ella wants to play the videos in slow motion to detect and transmit details she plans to focus on that day, so she adds a knot to set a very slow speed for the timeline's playback.

As the creation progresses, Ella defines additional floorplans for new sequences by cloning the border of the first floorplan in order to reuse its structure. She fills the new floorplans with new trajectories as they develop them in the studio. Ella even represents the trajectories of the imaginary rock rather than the dancers' bodies, so they can visualise the rhythm and react on time.

Ella also sketches the most representative aspects of each movement, and adds a portal knot to each in order to specify more detail. Each time the dancers come up with a variation to the movements, they film each other with their phones. Those who have iPhones send the clips via Apple's *AirDrop* to Ella, and the others send them by email when they get access to internet. Whenever she has the time, Ella imports the clips into *Knotation* to keep track of the changes, inside the corresponding portals.

DESIGN DESCRIPTION

Sketching multi-stroke choreographic objects

Knotation automatically groups the user's pen strokes into choreographic objects, based on a combination of temporal and spatial proximity[12]. When the user taps a choreographic object, it gets highlighted, so the user knows its scope. Actions such as *move*, *clone*, and *delete*, can be applied to single or multi-stroke choreographic objects. This allows the user to sketch freely without having to move a complex drawing stroke by stroke.

Adding functionality: Knots, attributes, controllers

The user can add functionality by placing the pen on the surface and long-pressing, which produces a small dot or *knot*. Knots can be created in the flow of writing or drawing, at the beginning, middle or end of any pen stroke. The user can add interactive features by tapping a knot and selecting the desired function from a circular menu (Fig. 58). Knots are first-class objects that can be moved, cloned, edited, or deleted. They are coloured according to their type, and the most relevant have representative icons to further facilitate recognition.

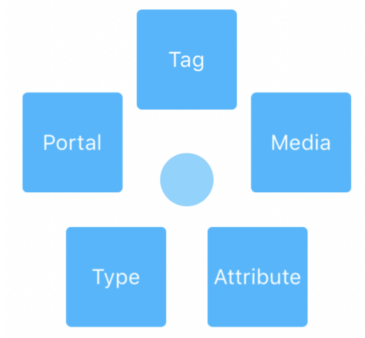


Figure 58: *Knotation*: Tapping a newly-created knot reveals the menu of available features.

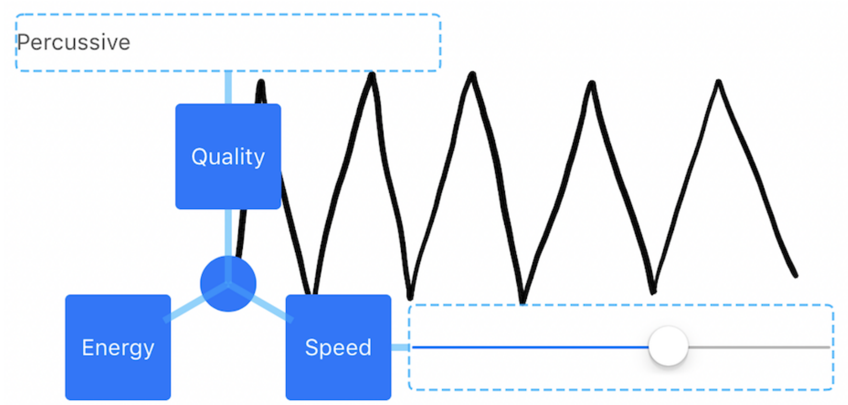


Figure 59: *Knotation*: Knot attached to a zigzag trajectory. Tapping the knot reveals three attributes: *quality*, *energy* and *speed*. Here, the knot defines a *"percussive"* quality, with a slider to indicate speed.

12 Allowing the user to add or remove strokes from a grouped object is still work in progress, as well as implementing a "fresh ink" metaphor to indicate which strokes belong to the object being drawn.

Knots can have multiple *attributes* (*speed*, *energy*, *duration*, and *quality*), whose values are set via a *controller* (a *number*, a *slider*, or *text*). Fig. 59 shows a knot where the user assigned a text controller to the *quality* attribute and typed *"percussive"*, and added a slider controller to the *speed* attribute. To reduce visual clutter, the attributes assigned to a knot only appear when the user interacts with it. In addition, *Knotation* provides *dancer* knots to represent dancers, with an optional name, and *tags* for labelling knots.

Incorporating media content

The user can link a knot to any image or video file in the photo library. For example, a choreographer might want to sketch a floorplan and attach a rehearsal video of the corresponding section of the piece: The choreographer can simply add a knot to the border of the floorplan, and link it to the video file. Then they can play the video by tapping on the knot; a second tap stops and hides the video. The user can reposition both videos and images by dragging-and-dropping with the finger, and adjust the size with a pinch gesture.

Composing the space: Floorplans

Knotation provides the *floorplans* identified in the studies with choreographers and dancers (Chapter 6), where users define movement through space using trajectories. Creating an interactive floorplan begins by drawing a closed (or almost closed) area and attaching a floorplan knot. The border turns orange, indicating that the figure is now interpreted as an enclosed two-dimensional space. Any strokes within this figure are considered *trajectories*, which are also rendered in orange.

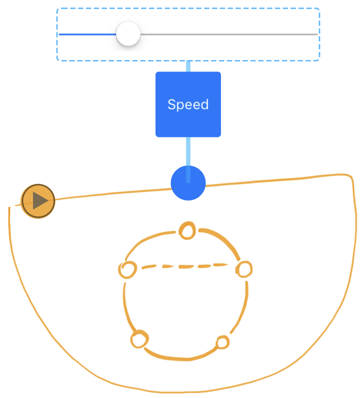


Figure 60: *Knotation*: A floorplan with a *speed knot* controlled by a slider.

Tapping on the floorplan knot animates each trajectory in the direction in which it was drawn. Users can modify the speed of the trajectories by attaching a *speed knot* (a knot with a speed attribute) to the floorplan's border (or to a specific trajectory), and either entering a numeric speed value or adjusting a slider, as shown in Fig. 60[13]. Alternatively, users can apply a *duration knot* to specify the duration of a specific trajectory, or of all the trajectories on a floorplan. When attaching a duration knot to a floorplan's border, *Knotation* calculates the speed of each trajectory in the floorplan such that they all finish at the same time. Since both speed and duration cannot be active at the same time in a given

13 The content of a text controller only has an effect if the system can interpret it as a number, e. g., if the user types "2.5". The system does not try to interpret values such as "slow", but the user could, for example, add a textual tag to the knot to remember that "slow" means "2.5".

floorplan or trajectory, only the attribute of the last attached knot is enabled; the others are greyed out. If a trajectory has an individual speed or duration knot, this knot takes priority over the floorplan's.

Users can move floorplans, including any trajectories and knots, by simply dragging the border with one finger. Users can incorporate a set of strokes into a floorplan by dropping the floorplan over the strokes, which causes *Knotation* to interpret them as trajectories. Users can create a reusable floorplan template by cloning its border. *Knotation* clones the floorplan's properties, i. e. its attached knots, but not the interior trajectories. To detach a floorplan from its contents while keeping its properties, users can drag the border with two fingers and move it elsewhere. The associated trajectories are detached from the floorplan and become normal strokes, rendered in black.

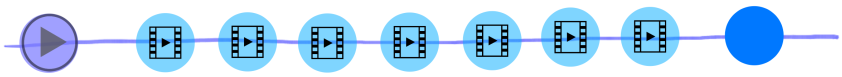


Figure 61: *Knotation*: A timeline with video knots and a speed knot.

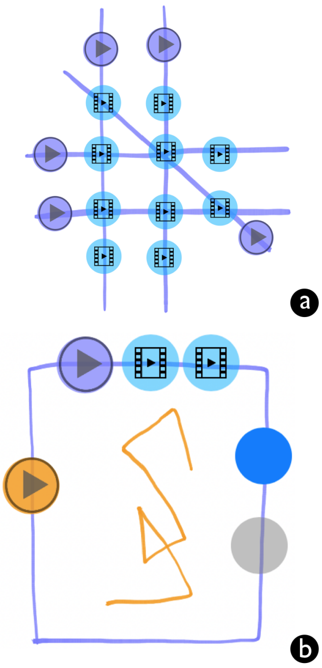


Figure 62: *Knotation*: Video knots can belong to multiple timelines (a). Combined floorplan (orange) and timeline (violet) (b).

Composing the time: Timelines

Knotation introduces interactive *timelines* to let choreographers define temporal sequences. Creating a timeline consists of drawing a stroke of any shape and attaching a *timeline knot*, which turns the stroke violet. Users can then add any type of knot to the timeline (Fig. 61). Users can also create a new timeline by drawing a stroke across an existing set of knots and attaching a timeline knot to the stroke. This allows the user to create a constraint from a set of existing objects — just as in *StickyLines*, but with temporal constraints instead of spatial ones.

Tapping on the timeline knot displays the video knots in the order specified by the direction in which the timeline was drawn. The timeline plays the videos either at normal speed or at a speed determined by a speed knot. Users can reorder, edit, clone, attach, detach or delete knots, even as the timeline plays. Fig. 62a illustrates how a single video knot can be attached to multiple timelines, which, for example, lets users explore different combinations of fragments in different orders.

As with floorplans, users can move timelines and their attached knots by simply dragging the timeline stroke. Users can create reusable timeline templates by cloning the stroke. They can add new knots to the blank timeline, reusing its shape, speed and any other attributes, which *Knotation* clones automatically.

Combining time and space

Users can also combine floorplans and timelines into a single choreographic object, as shown in Fig. 62b. However, users are not limited to floorplans and timelines: They can create their own choreographic objects, with different characteristics, and attach knots to them.

Detailing or abstracting choreographic objects: Portals

Users can create *portals* that provide a link from the original choreographic object to a more detailed or more abstracted view of it. The user adds a *portal* knot and taps it to create a new canvas. The user can return to the original object by tapping on the portal knot that appears automatically at the top of the new canvas. Unlike other knots, cloning a portal does not generate a copy, but instead provides alternate access to the same object.

Establishing relationships between choreographic objects

To increase user control and enrich exploration, *Knotation* includes the concept of *relationship* between choreographic objects. One important type of *relationship knot* is *order*, which can take two values: *simultaneous* or *sequential*. This relationship can be used to control the order of a set of events in timelines and floorplans. For example, if the user adds a *simultaneous order* knot to a timeline, videos will be played all at the same (Fig. 63a). Adding a *sequential order* knot to a floorplan results in the trajectories being animated one after the other, in the order in which they were added to the floorplan (Fig. 63b).

Knotation also allows the user to set other two types of relationship knots for specifying relative movement: *mirroring*, to indicate that two groups of dancers mirror each others' movements; and *unison*, to indicate that several dancers perform a movement simultaneously[14].

14 Unlike *order*, these two relationships do not have an effect on choreographic objects in the current version, beyond annotation — adding interactivity to them is left for future work.

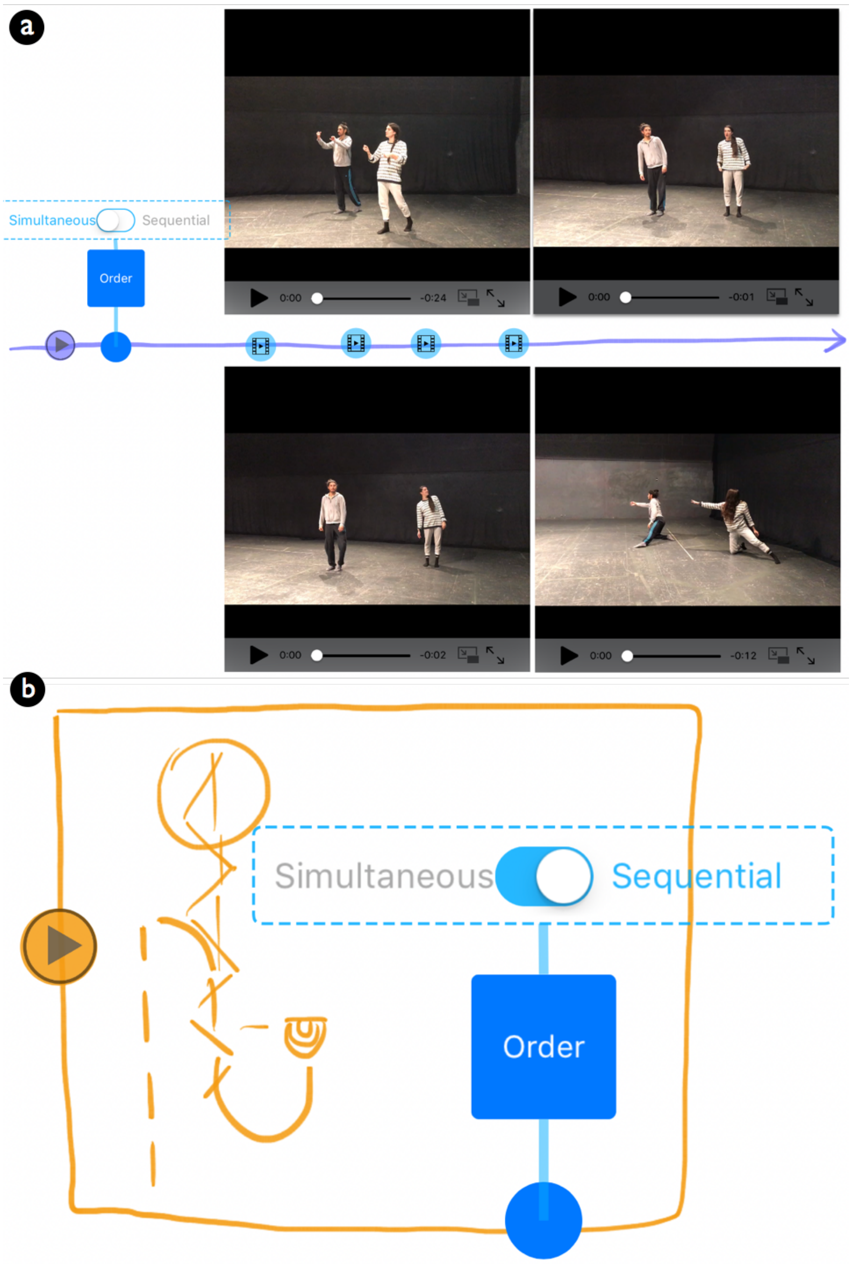


Figure 63: *Knotation*: Playing multiple videos at the same time with a *simultaneous* timeline (a). Animating trajectories one by one in a *sequential* floorplan (b).

In summary, *Knotation* lets choreographers:

- compose the space, time and structure of a piece by sketching interactive *floorplans* and *timelines*;
- create multiple views at different levels of abstraction and link them via *portals*; and
- represent movement constraints via *attributes* and *controllers*.

COMPARISON WITH KNOTTY GESTURES

Comparing *Knotty Gestures* and *Knotation* involves considering two main factors: the medium in which they work (paper versus tablet) and the goal (augmenting annotations versus supporting exploration and documentation of the choreographic creative process).

Regarding the medium, a great advantage of interactive paper over tablets is that today's choreographers are still more familiar with paper. In addition, interactive paper is highly flexible, lightweight, portable, and its (static) content is always available, but the user needs to buy new interactive paper sheets as they get filled. Assuming that the user already owns a computer, the price of an interactive pen and sheets of interactive paper is still considerably lower than the price of an iPad Pro and its pen, but *Knotation* could be implemented for cheaper tablets in the future[15]. In terms of portability, carrying around a tablet and a pen in a dance studio is easier than a computer, a pen, and paper.

On the other hand, because *Knotation* runs on a digital environment, digital knots and strokes have several advantages over their paper versions. It is no longer necessary for the user to draw each knot by circling with the pen: Creating a knot through a gesture as simple as long-pressing with the pen eliminates recognition problems. Moreover, an important design decision I made is that in *Knotation*, knots can live on their own, they are no longer "parasites" of drawn strokes. This allowed me to design digital knots as first-class objects (rather than modifiers of other objects) that the user may move, clone, or delete. While physical ink leaves permanent traces on paper, digital ink lets the user erase these traces when desired, or even enter modes in which the pen leaves no traces at all.

The characteristics of the Anoto pens and the setting posed constraints upon the interactions available in *Knotty Gestures*. For example, to select functionality, the user had to circle around the knot in order to display one option after the other on the pen's screen. In *Knotation*, the user interacts directly on the iPad's

15 Currently, it also runs on devices with MacOS, via iOS simulators.

screen, so designing menus that show all the relevant options at once is less challenging. I opted for circular contextual menus whose items depend on the tapped object. In *Knotty Gestures* knots are "nested" to reduce the number of available options to choose from on the pen's screen. As in *Knotation* this is not a problem, I did not need to include nesting in the design. As a general rule, I tried to design interactions that apply to all or most types of objects on screen. When this is not possible, knots over incompatible objects are displayed in grey to indicate that they are not active.

Knotty Gestures is particularly convenient for interactions where the Anoto pen can augment the annotations on its own (for example, by showing the result of a mathematical operation on its screen, or by playing a simple audio cue or a short voice recording). However, actions such as playing a video are performed on the computer's screen, which is spatially decoupled from the knot that triggered the action, and thus from its context on the paper. Basing the interaction on a tablet allows embedding different types of data in the same document, centralising the user's attention on one place.

Regarding the goal, a fundamental difference between *Knotty Gestures* and *Knotation* is the type of handwritten content they target. *Knotation* focuses on sketches and how to make them interactive, while *Knotty Gestures* is an in-the-flow-of-writing technique to augment handwritten annotations, including text, mathematical formulas, and music scores. Because of this, the traces of interaction in *Knotty Gestures* are more subtle: They are limited to tiny knots (sometimes with marks or tails) to indicate that an interaction is available at that point. This design decision assumes that hiding the details is a desirable behaviour, which might not be the case in choreography composition. In *Knotty Gestures*, the pen strokes under a knot give context to the system for triggering the right action. In *Knotation*, strokes themselves become interactive through the use of knots: The user can actually sketch their choreographic objects, define their functionality with knots and fine-tune it.

DESIGN DECISIONS AND CHALLENGES

Knotation is not a paper notebook, a graphical editor, a word processor, or a spreadsheet application, although it has aspects of the four. It was challenging to design it in such a way that allowed users to handwrite, sketch, type in text, and establish relationships between objects, without offering too many, too heterogeneous features. In addition, making decisions regarding choreographic knowledge was not trivial. For example, choosing example attributes for knots was hard, as the vocabulary used by choreographers is diverse and often personal. For this reason, I chose two that were easily implementable in the system (speed and duration) and other two that are widely used and can be interpreted by users (energy and quality). Initially, I wanted to let the user define their own attributes, and even organise them into hierarchies (for example, creating subtypes of qualities), but I had to prioritise the design and development of other more novel concepts, such as *Knotation*'s floorplans and timelines.

As *StickyLines*, the design of *Knotation* avoids the use of interaction modes. Spatial modes consume space and often imply dividing the screen into sections that the user needs to learn how to use. Temporal modes require switching to activate and deactivate them, confusing the user if it is not clear which is the present mode or if they forget to switch. I also chose not to use interface elements that make interaction clunky or clutter the screen (e. g., dialogue boxes, inspectors, global palettes, linear menus, etc.), and I tried to leverage direct manipulation instead, given the iPad's input possibilities. *Knotation* supports both finger and pen interaction: The pen draws persistent strokes, whereas the fingers move sketched objects and access associated menus. For reasons of precision, the pen can also drag knots and invoke their menus.

In terms of technical aspects, managing video was challenging because of restrictions imposed by the AVFoundation kit. For example, only a number of videos can be displayed at the same time, and this number varies from execution to execution, thus cannot be predicted. In addition, automatic notifications indicating that a video finished playing (which is required to, for example, trigger the display of the next in a sequence) would sometimes get lost when several played at the same time, especially when different speeds were involved.

7.3 TECHNOLOGY PROBE WITH THREE CHOREOGRAPHERS

Near the beginning of the design process, we introduced a minimalistic version of *Knotation*, called *Knotation v1*, as a technology probe (Section 1.2.3) with three choreographers, to observe how they would express their choreographic ideas and constraints, and make them interactive. We wanted to extend our understanding by focusing on the capture of inspiring practices and appropriation cases, as well as triggering and discussing ideas with participants.

Participants: We recruited three France-based professional choreographers (two men, one woman), with four to 34 years of experience. All use one or more of the following to record their work: paper, video, word processing, and graphical editing tools.

One participant was the lead choreographer in the observational study from Chapter 6.

Hardware and software: The study used *Knotation v1* running on a 12.9″ iPad Pro™ with iOS 10.2, and an Apple Pencil™ for input. *Knotation v1* was implemented in Swift 3 and used Apple's AVKit and AVFoundation frameworks to manage video (in particular, the AVPlayer controller object). It relied on default gesture recognisers to handle user input from fingers or the pen, to recognise tap, pan, pinch, and long-press gestures. I used two ad-hoc gesture recognisers: one for panning with the pen (which generates drawn strokes) and one for long-pressing (which creates a knot). To spark design conversations with participants, *Knotation v1* purposely offered minimal functionality. It did not provide access to previous versions of the document. Each drawn stroke was interpreted as a separate choreographic object and could not be moved. Floorplans and timelines were not interactive yet: Adding a floorplan or timeline knot to a sketch did not have any consequence. Similarly, speed and duration knots did not affect the sketches either. It did not include dancer knots, tags, or relationships; knots were all blue (except for portals, which were green) and they did not have icons.

Setup: I conducted each session in a local dance studio, which had chairs, a bench and a table. Participants could use the tablet in any position, including standing up, on the floor, or on a table. My advisors attended the sessions and participated in the debriefings. Sarah Fdili Alaoui, who is a trained dancer and choreographer, also served as a volunteer dancer. Two members of our research lab attended the first session to help with the setup and filming.

Procedure: Each session lasts approximately two hours. The participant receives a live, 2.5-minute scripted demonstration of *Knotation v1*'s functionality. Next, they play with the tool until they feel comfortable, up to 5 minutes. We answer questions regarding the available functionality. Activity 1 involves the *composition* of a short choreographic fragment for about 30 minutes. The participant is asked to pick a current piece to increase engagement and to encourage recall of recent, rich details about the choreographic content. The participant chooses when and how much to use *Knotation v1* and can also use paper to document their work. After a 10-minute break with healthy snacks, they begin activity 2, which involves the *transformation* of the composed fragment for about 30 minutes. The participant can define transitions, reorder parts, structure the fragment, etc. The session concludes with a 15-minute debriefing session where the participant explains their choreographic objects, followed by a 10-minute interview.

Data collection: We placed a camera on a tripod behind each participant to record video and audio of each session, and also took pictures, close-up videos, and written notes.

Data analysis: I translated the raw data to English, as two of the three sessions were conducted in French. I analysed my notes, pictures, and videos, in order to find common patterns across participants, capture inspiring practices and identify examples of appropriation that might trigger new design ideas.

7.4 RESULTS AND DISCUSSION

P1 choreographed a fragment for four dancers; P2 worked on a solo that was performed by our volunteer; and P3 produced two fragments: First, a solo that he performed, and then a duo for himself and our volunteer.

CAPTURING MOVEMENT OR CAPTURING CONSTRAINTS

I identified two contrasting strategies among participants who focused either on concrete movements or on the rules that define them. P3 documented the particular movements he had composed, through video and textual notes. By contrast, P1 only documented and transmitted the constraints the dancers had to meet in order to perform the fragment. P2 did both: He manipulated video knots from the choreographic fragments he recorded, and played with attributes to capture the rules behind them.

During the *composition* activity, P1 asked four research team members to serve as volunteer dancers. She explained her main choreographic object: Two performers form a *"wall"* by moving sideways along a diagonal, while the other two close their eyes and move, with the *"follower"* trying to mirror the movements of the *"leader"*. She then filmed the four performing the fragment. Finally, she used *Knotation v1* to create an alignment relationship between the two *"wall"* performers (Fig. 64). She drew a diagonal line with arrows to indicate the possible directions of the movement, but did not define the concrete trajectories that the performers had to follow. She also drew a *"plane"* of dots at both sides of the diagonal, to indicate the area in which the other two were allowed to move.

VARYING THE STRATEGY ACCORDING TO THE TYPE OF PIECE

One participant adopted two distinct strategies for recording ideas, according to the type of piece. At the beginning of the session, P3 worked on a fragment of a contemporary dance piece he was revising. He used *Knotation v1* to create an *"index"* or overview of the piece, which consisted of a vertical list of tex-

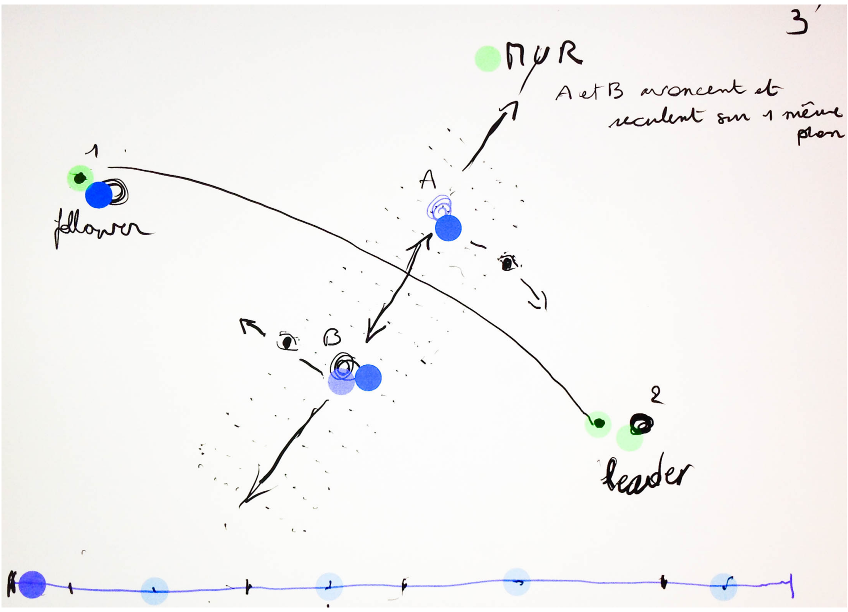


Figure 64: Technology probe study: Representing constraints with *Knotation v1* (P1).

tual elements corresponding to each part of the choreography. He marked[16] several phrases to remember the details. He created one knot per item and per transition and then filmed several elements which he linked to the knots. He considered defining his *"index"* as a timeline, but decided against it, remarking that it was more of an *"ordering"* than a timeline. When he began annotating a tango fragment, P3 changed his approach, switching to his own formal notation and video knots to annotate the phrases. His system represents each tango step as a symbol (an example is shown in Fig. 65). Both partners use the same score: The leader reads the string of symbols from left to right, and the follower stands in front and reads them from right to left (Tripodi, 2017).

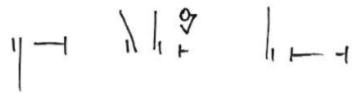


Figure 65: Basic tango step in parallel system, written in Matías Tripodi's notation. Source: Tripodi (2017).

Figure 66: Technology probe study: Using *Knotation v1* to transmit an improvised dance sequence.

USING KNOTATION FOR IMPROVISATION AND TRANSMISSION

P3 appropriated *Knotation v1* in a creative way: He asked the volunteer dancer, who had never danced tango, to perform several phrases with him, holding the iPad between them (Fig. 66). He then wrote a symbol for each step, which they read in silence as they performed, improvising the choreographic fragment.

16 Kirsh (2011b) defines *marking* as *"execut[ing] a dance phrase in a simplified, schematic or abstracted form"*.

APPROPRIATING PORTALS TO DEFINE RELATIONSHIPS

Instead of using portals to record additional detail about a choreographic object, P1 cloned them to establish a relationship between two dancers and indicate that they had to perform the same movement. Similar to designers in Part I viewing stickylines as relationships, P1 saw portals as more than mere tokens to trigger actions, using them instead as a way to establish and visually indicate a persistent relationship.

TRIGGERING INTERACTION IDEAS

Once their choreographic ideas became interactive, participants sought additional ways of interacting with them. For example, P3 suggested that, when attaching a video knot to a trajectory, the user could trace the trajectory with the pen to advance or rewind the video, which would link two views of the same choreographic object, one in 2D and the other in 3D. P2 would like to personalise the hierarchy of attributes. He identified the need of *"showing the arborescence"*, in order to *"hierarchically organise the scenes"* in a piece[17]. P2 also wanted to create his own toolbox of reusable instruments. For example, a triangular *"focus tool"* that could be rotated to point in the desired direction. P1 wanted a *"general timeline of the piece"* — as timelines were not interactive in *Knotation v1*.

REVEALING THE MEANING OF A KNOT

The knots in *Knotation v1* hid the details of their associated functionality to avoid cluttering the screen. However, participants wanted the opposite: to reveal their meaning. P1 wanted the knot to appear as an icon indicating its content, e. g., a video icon for a video knot. P2 and P3 wanted different colours for different types of knots, for easy identification.

REFLECTING ON THE TOOL AND THEIR OWN PRACTICES

P1 appreciated that *"the way of representing the ideas"* in *Knotation v1* made her *"reflect on what is possible"*. P3 said that although he relies on his memory or makes long videos of his fragments, *Knotation v1* made him *"want to film [each part] and play with the videos"*. He also added that *"the tool could definitely help"* him during his creative process to create a *"stable grid"* to organise his work because otherwise he is *"chaotic"*. Interestingly, all participants mentioned that *Knotation v1* could be also used for organising the lighting, either by themselves (P1, P2) or by light technicians (P3).

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17 We had already designed these two features by the time of running this study. However, they were not a priority as we wanted to explore novel concepts that were more specific to choreography.

7.5 SUMMARY

We observed diverse exploration and documentation strategies that captured only movement, only constraints, or a combination. Once participants were able to express their choreographic ideas in *Knotation v1*, they sought additional ways to interact with them. They appropriated the available functions, and proposed specific new features. Interestingly, participants wanted knots to reveal their characteristics, rather than just encapsulate functionality, which suggests they saw knots as a way to add *personal meaning* to their sketches.

This technology probe study offered three types of results:

- *Empirical*: the introduction of the concept of knots encouraged participants to explore additional possibilities for expressing movement, constraints or both;
- *Design*: in addition to suggesting specific features such as colour and knot icons, participants sought to embed interactive constraints within their choreographic objects; and
- *Technical*: we identified bugs (which lead to an auto-save feature), technical challenges (e. g., optimising stroke rendering) and ways to simplify common operations (e. g., deleting objects).

7.6 STRUCTURED OBSERVATION WITH SIX CHOREOGRAPHERS

The results from the technology probe study influenced the design of *Knotation v2*: I focused on turning floorplans and timelines into first-class interactive objects, and allowing users to move and clone any object on the screen. I also added a number of features specifically requested by study participants.

Knotation v2 is designed to provide choreographers with a lightweight technique for quickly sketching choreographic ideas, capturing video examples, exploring constraints, and recording the result in a form that can be transmitted to dancers or other collaborators. I was interested in probing for user strategies in the context of integrating the tool into realistic choreographic activities, so I used a structured observation (Section 1.2.4) approach to further study choreographers' practices.

Participants: We recruited six professional contemporary choreographers (five women, one man), with a range of three to 47 years of experience (median: 16). P1 brought a fellow choreographer (P1C) and they worked as a team for each activity. In their choreographic practice, all participants sketch on paper and use video to record themselves or dance rehearsals (although the latter is rare for P1). P3 and P5 also edit their videos. All but one participant were based in Paris, France. My research lab covered travel expenses for the non-local choreographer, and lunch for all participants at a restaurant.

Hardware and software: The study used *Knotation v2* on a 12.9″ iPad Pro™ running iOS 10.3, with an Apple Pencil™. In *Knotation v2*, floorplans and timelines were interactive. Speed and duration knots affected timelines and floorplans, but could not be set at the level of individual trajectories yet. The user could move, clone, or delete any object on the screen, but sketches were still single-stroke. The following enhancements to the first version were directly based on participants' feedback from the technology probe study:

- *coloured knots*, according to type;
- *icons* representing video and image knots;
- *dancer* knots, with optional names;
- *tags* for labelling knots;
- *relationship attributes* for specifying relative movement, with two examples: *mirroring*: when two groups of dancers mirror each others' movements, and *unison*: when several dancers perform a movement simultaneously.

Setup: I conducted three sessions with two participants each at a local dance studio. Participants could move freely in the studio, which had a bench, chairs, and a table. Each participant received an iPad with *Knotation v2*. My advisors attended the sessions, and Sarah Fdili Alaoui acted as a volunteer dancer.

Procedure: Each session includes five activities: *training*, *composition*, *transmission*, *transformation*, and *debriefing*, and lasts between two and three hours. The three middle activities are designed to reveal how *Knotation v2* supports initial creation (*composition*), documentation and communication of choreographic ideas (*transmission*), and edition of existing ideas (*transformation*).

1. Training (up to 30 minutes): Both participants receive a live, eight-minute scripted demonstration of the main features of *Knotation v2*. Next, they play with *Knotation v2* on their assigned iPad until they feel comfortable, asking questions as needed.

2. Composition (30 - 60 minutes): Participants create a brief choreographic fragment for one or more dancers. They choose when and how much to interact with *Knotation v2*. The researchers and participants decide together when to transition to the next activity, after at least 30 minutes.

3. Transmission (15 minutes): Participants take turns explaining to each other the fragments they just composed, and asking each other questions.

4. Transformation (30 - 60 minutes): Participants are shown two artefacts that choreographer Anne Teresa de Keersmaeker uses to transmit her piece *Drumming Live*: a publically available video fragment, and a printed illustration of the golden rectangle that serves as the floorplan (Fig. 67). Participants choose a choreographic element from the video or floorplan and modify it to match the style of the fragment they just composed, for at least 30 minutes.

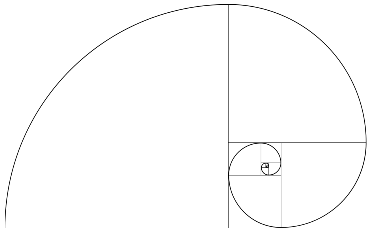

Figure 67: Structured observation with *Knotation v2*: Participants receive the golden rectangle as a prompt.

5. Debriefing (15 minutes): Participants explain the choreographic objects they created.

Data collection: We placed a camera on a tripod in the corner of the studio to record each session. We also took close-up videos, photographs and hand-written notes, and logged the participants' interaction with *Knotation v2*.

Data analysis: I translated the raw data to English, as four participants spoke in French, and one in Spanish. I analysed my notes, pictures, and videos. I also compared participants' practices within and across activities.

7.7 RESULTS AND DISCUSSION

Most participants (5/6) shot video of their movements with the iPad; two participants (P3 and P4) also imported images. They all left their iPads on the floor or occasionally on their laps, picking them up only when they stood to capture a dance movement. During the *transmission* activity, participants gathered around the iPad on the floor to explain their compositions to each other. They pointed to their floorplans and timelines, played videos, gestured over the iPad, and occasionally marked specific movements.

Next, I present two kinds of findings: insights about participants' choreographic approaches, and insights about the use of *Knotation v2*.

DIVERSE CHOREOGRAPHIC APPROACHES

All participants successfully created a novel idea for their choreographic fragment, using personal composition strategies. For example, P1 started with two concepts — *"the sane"* and *"the crazy"* — and collaborated with P1C to write notes and sketch symbols with *Knotation v2* and to shoot six *"elements"*. Together, they experimented with changing the order and number of repetitions on a timeline.

We identified common approaches across participants (see Table 1). Two participants (P2, P4) used a *"dance-then-record"* approach, dancing first and then capturing the result with *Knotation v2* at the end. For example, P4 immediately started dancing and testing a variety of movements. After several minutes, she asked a researcher to record her as she danced each movement. She used *Knotation v2* only at the end to capture her fragment.

P3 used the opposite approach — *"record-then-dance"*. She sat on the floor thinking for several minutes, while using *Knotation v2* to plan different combinations of trajectories and movements. She then asked the volunteer dancer to perform a set of *"keyframes"*, which she recorded with *Knotation v2*. The other participants (3/6) went back and forth between dancing and using *Knotation v2*.

After watching the *Drumming Live* video during the *transformation* activity, all participants used the same approach they had adopted for the *composition* activity. However, all spent considerably more time interacting with *Knotation v2*, to check their earlier content and explore various novel transformations.

EXPRESSING DIFFERENT DEGREES OF FORMALITY

Multiple participants said they explicitly chose a particular level of formality and detail to represent their choreographic objects. P4 said she was purposely imprecise when annotating her fragment and appreciated how *Knotation v2* offered her various degrees of (in)formality: *"For me, since I love informal things, it works, but it also works for something more formal, more precise"*. P1C also noted that it permits *"being informal"*, thus *"stays open to interpretation"*.

INTEGRATING TIME AND SPACE WITH LINKED CHOREOGRAPHIC OBJECTS

One participant (P5) created a complex structure with floorplans and timelines to compose time and space. She drew one floorplan and timeline per dancer (Fig. 68), with *"properties"* (e. g., unison relationships) that are read vertically as in a *"rhythmic score"*. This served as a *"tool similar to the timeline"*, *"easily visible"*, that reveals *"what should happen at a given moment for each dancer"*. She created tagged knots and attributes for each timeline that indicated the scope of specific constraints over time (e. g., the direction of the dancer's gaze). She also cloned portals to define *"shared scores"* for dancers at the proper locations on their timelines. In addition, she drew a curve over each timeline to represent the levels with respect to the floor. She said she was trying to *"visualise the relationships in space between the dancers [in the floorplans], and then the relationships in time, by reading them vertically"* on the timelines. P5 thus created her own sophisticated structure for decomposing and combining the three spatial dimensions and time on a 2D surface.

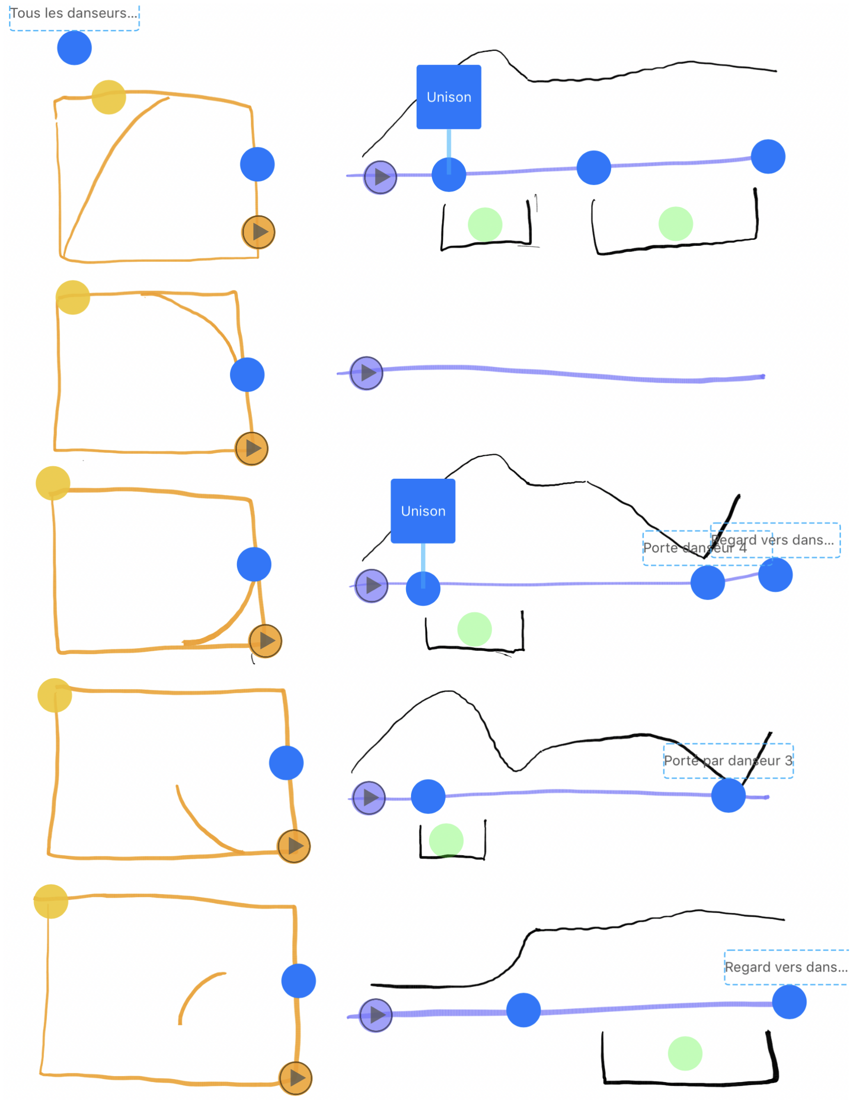

Figure 68: Structured observation with *Knotation v2*: P5 created pairs of floorplans and timelines, one per dancer, with progressive level changes. She also used knots to mark the scope of a particular constraint over time, and cloned portals to establish relationships among the dancers.

APPROPRIATING ERRORS TO DISCOVER PATTERNS

Some participants used errors to spark new ideas. P1 and P1C inadvertently linked several knots to the same video, which then led them to discover *"interesting patterns"* (P1C). P1C said that visualising the same element multiple times suggested new possibilities for interesting rhythms and dynamics, as well as novel *"extensions"* to the element. P1C commented: *"You don't find that in the videos you shoot!"*

ASSESSING CHOICES VIA CHOREOGRAPHIC OBJECTS

Participants interacted with their choreographic objects, for example by playing or repositioning timelines and floorplans or refining their attributes, to consider alternatives. P3 and P4 emphasised the importance of expressing a range of interconnected ideas before making choreographic choices. P1C described how she and P1 used timelines *"to see the available choices"* and suggested using *Knotation v2* as a way of *"validating things before testing them"* in the studio. P5 liked to *"see what were all the possibilities, because when you're trying to write [a piece] on paper, you can't pass from paper to video, or paper to duration"*.

USING KNOTATION V2

approach	**id**	**actions**	**knots**	**attributes**	**timelines**	**play TL**	**floorplans**	**play FP**	**portals**	**images**	**videos**
record-then-dance	*p3*	1531	94	10	7	0	4	7	7	25	9
mixed	*p5*	1142	77	21	7	0	9	53	7	0	3
	p1	426	24	2	4	2	1	12	2	0	9
	p6	1294	41	10	9	0	10	50	3	0	0
dance-then-record	*p2*	735	26	8	1	6	3	25	3	0	2
	p4	676	29	7	2	0	4	38	2	5	3

Table 1: Structured observation with *Knotation v2*: Number of actions and use of key features, grouped by choreographic approach.

A quantitative analysis of the logs (Table 1) reveals that P3, who used the *record-then-dance* approach, performed more than double the actions and created over three times as many knots as P2 and P4, the two *dance-then-record* participants. This correlation suggests a testable hypothesis: The *record-then-dance* approach is a cognitive-first strategy that favours a technology-mediated exploration of choreographic ideas, while the *dance-then-record* approach is a dance-first strategy where the technology supports documentation.

Most participants (5/6) imported and played video. Interestingly, P5 played one video once, and experimented instead with attributes, controllers, floorplans and timelines, which let her focus on defining higher-level structures.

All participants created at least one timeline (mean: 4.3), although the *dance-then-record* participants only created one or two. Surprisingly, most participants (4/6) did not play their timelines, even though they added and removed knots from them multiple times. This suggests that they used timelines as a grouping mechanism, obviating the need to play videos in their final order. This is similar to how designers used *StickyLines* to group objects while structuring graphical layouts.

All participants created at least one floorplan (mean: 5.2) and interacted with floorplans considerably more frequently than with timelines (mean: 30.8). In particular, P5 interacted repeatedly with knots to establish speed and duration.

Participants created from two to seven portals each. Although P3 and P5 created slightly more, we found no differences across strategies with respect to use of portals.

APPROPRIATING FLOORPLANS AND TIMELINES

Figure 69: Structured observation with *Knotation v2*: P6 created a timeline whose shape represented a spatial trajectory.

Participants found several creative new uses for floorplans and timelines. For example, P1 and P1C overlapped clips to make them appear as a single seamless video in the timeline. P2 drew short trajectories near, but just outside the border of a floorplan, to avoid animation and indicate that the dancer began and ended the sequence off stage. P3 used floorplans to define *"keyframes"* (diagrams showing each dancer's location at a given moment as seen from above) and represented dancers with knots and transitions with lines. P6 went further, combining the concepts of floorplans and timelines: She drew a spiral-shaped timeline where the shape represented a spatial trajectory (Fig. 69). She also redefined the meaning of trajectories within her floorplan. For example, she wrote five words with a corresponding set of symbols, one for each of five floorplans. These symbols represented trajectories *"but not in a horizontal floorplan space"*.

PARTICIPANTS' FEEDBACK

Several participants highlighted how well *Knotation v2* supported diverse choreographic processes. In particular, P3 noted that even though she and P4 used extremely different approaches, *Knotation v2* supported them both. P4 emphasised that *"it does not impose a method... I like that very much of this piece of software"*.

Participants liked *Knotation v2*'s ability to gather diverse material about a project. P1C said that it was *"really interesting to be able to gather imagery easily, that is instantly playable, with your hypothesis of time and space"*, and finds *Knotation v2* *"a file easy to rework, to be brought up again"*. P1 liked that *"instead of having fifteen thousand notes, you have it here all assembled"*. P3 explained that, for her, there is a *"time of creation"* and a *"time of technology"*, and that *"a tool like this allows you to join those times"*. Interestingly, P4 suggested a new name, *"Knowtation"*, to highlight its ability to collect knowledge about a piece. By contrast, P1 felt that having *"so many possibilities"* constantly *"triggered new ideas"* before he could process his previous ideas, so he *"got entangled"*.

Participants suggested a number of possible features, such as grouping timelines and floorplans. They also noted several limitations. P2 mentioned she wanted *"to keep everything visible"* but the screen size was an issue, although she noted: *"I have the same problem with the computer"*. P3 wanted to use portals to visualise the tree-like structure of a piece. She would also like to reshape an existing timeline into a circle to represent a loop[18]. P4 was interested in exploring acceleration, so we discussed the possibility of adding speed controllers defined by functions — for example, an exponential curve drawn by the user and manipulated similarly to *StickyLines*' distribution curves.

7.8 SUMMARY

Knotation v2 supported participants with diverse choreographic approaches, including *dance-then-record*, *record-then-dance* or a combination of the two, without imposing a particular process. Participants were able to assign personal meanings to both their input and the system's feedback, and change their minds over time. They also chose their desired level of formality, from informal sketches to formal notations. The structured observation approach generated a testable hypothesis: A *record-then-dance* approach most enhances exploration of choreographic ideas, while a *dance-then-record* approach favours documentation.

18 As I did not have evidence of choreographers needing such feature, I had not included reshaping capabilities in *Knotation*. In fact, this feature exists in *StickyLines* and was creatively used by designers.

Participants combined timelines and floorplans to represent their choreographic objects, including both simple and complex temporal and spatial structures. Interestingly, they appropriated their errors to explore novel choreographic patterns. This study demonstrates the potential of *Knotation v2* as a mobile tool for exploring and documenting choreographic ideas in a studio setting, and offers new insights into the choreographic creative process.

7.9 DISCUSSION: DESIGN PRINCIPLES

The design of *Knotation* follows Shneiderman's (2007) guidelines for CSTs:

- *it facilitates exploratory search*, as users can make their creative constraints explicit and manipulate them directly by playing with floorplans and timelines' attributes — e. g., speed and duration;
- *it supports the generation of multiple alternatives*, as users can create and clone their choreographic objects and organise them in different configurations that are visible at the same time, for example, adding video knots of dance fragments to multiple timelines, or visualising a set of floorplans with slightly different trajectories;
- *it provides a rich history*, as users can go back to previous versions of the document;
- *it enables collaboration*, as it is a mobile tool that can be physically shared among collaborators, it does not impose a formal notation language requiring previous training, and it allows quick capture of in-the-moment ideas and dance sequences with dancers in the studio. However, its capabilities and limitations in this context should be further investigated, as collaboration was not the focus in the conducted studies. For this reason, I ran two longitudinal studies with choreographers and dancers using *Knotation* in their dance projects, which I describe in Chapter 8.

7.9.1 *Reification*

Timelines and floorplans are instruments that allow users to organise a choreography in time and space. They act upon users *content*: dance fragments in the case of timelines, and spatial trajectories in the case of floorplans. The parameters to control these instruments' behaviour are additional *constraints* explicitly defined by the user when attaching, for example, speed or duration knots. A timeline could be seen as an open stickyline, and a floorplan as

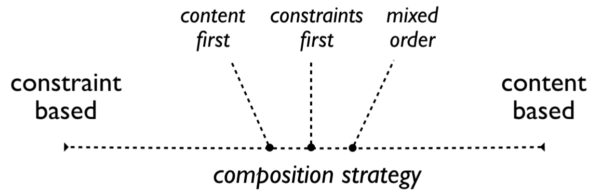

Figure 70: Continuum of composition strategies ranging from based on constraints to based on content, with three examples of orders.

a closed stickyline, as they keep knots attached respecting their relative positions, but over a more general shape than straight lines and ellipses.

Timelines reify the action of selecting and ordering a set of dance fragments in time (represented through video, but open to other representations in the future). By persisting this temporal order, they allow users to work with the set of dance fragments as a group. The fact that knots can be easily repositioned, attached, and detached from the timeline facilitates the exploration of the temporal structure.

Floorplans' trajectories reify the action of traversing space over time, by capturing the traces that the bodies would leave on the floor and visualising them as lines. Floorplans keep trajectories grouped and animate them according to the principles defined by the user, who can easily add or remove trajectories to explore different combinations.

Related timelines and floorplans could be reified into playable *groups* by linking them. The user could link the desired objects by drawing a line that joins them, and attaching a *link* knot to the line. Tapping on the link knot would play all the objects at the same time (or sequentially if adding the corresponding order knot). However, this behaviour is very similar to that of timelines: Making timelines able to play any type of visual or audio object would be enough to create groups.

Support for diverse composition strategies

In the two studies with choreographers using *Knotation*, we observed more varied strategies regarding constraints than those employed by designers with *StickyLines*. These strategies can be positioned on a continuum ranging from a *constraint-based* approach, to a *content-based approach*, according to what aspect the choreographer emphasises. At any point in between these extremes, users might employ a *constraints-first* strategy, a *content-first* strategy, or a *mixed-order* strategy (as exemplified in Fig. 70).

One participant from the technology probe study (P1) worked in a purely *constraint-based* manner: Unlike designers with *StickyLines* who *started* with constraints and then defined the content, she never documented the concrete movements that dancers had to perform. In her composition, dancers were free to move as they wanted inside the space defined by the choreographer's constraints[19]. Interestingly, we did not find cases of participants first starting with constraints and then populating their document with the concrete movements, but this is a perfectly possible strategy that would be feasible in *Knotation*.

In the other extreme, a participant in the technology probe study (P2) only documented the choreographic material he created, with a *content-based* strategy. We also observed that some participants in the structured observation (e. g., P2, P4) first tried trajectories physically, then drew them, and at the end decided to create a floorplan around them in order document the result and verify how the animation looked. This could be considered a *content first* strategy, as the one described in Section 5.10.1. These participants defined constraints with a documentation purpose, rather than to use them interactively during their current composition tasks.

Others (for example, P3 and P5 from the structured observation), created several floorplans beforehand, and then started drawing the trajectories while playing with the floorplans' attributes, which constitutes a *mixed-order* strategy in which content and constraints influenced each other.

Based on this diversity, I argue that digital tools for choreographic composition cannot be limited to only support constraints or only movement, if they want to avoid enforcing a particular approach upon the user. Tools should enable users to define both constraints and content and switch between the two at any point of the process, or even keep a blurred division between these concepts.

Collaboration potential

As with *StickyLines*, producing a persistent, interactive document of the dance piece enables the collaboration of a user with their future self, and serves as a support for transmitting the created material to dancers and other collaborators, as shown in the structured observation study. A more in depth examination, which I describe in Chapter 8, is needed to study the implications of *Knotation*'s use in real and not just realistic collaborative settings.

19 It would be interesting to observe how P2 and P6 from the interview study in Chapter 6 would use *Knotation*, given that they normally use a constraint-based composition method.

Instruments as objects of interest

Similar to *StickyLines*, the boundary between objects of interest and instruments in *Knotation* is also a blurred one, which gives more control to the user over the evolution of their content and constraints. However, although the interaction with floorplans, timelines and knots is based on simple actions (tap, long press, drag, pinch), the interaction with a digital pen and a tablet was not so familiar for choreographers as the use of the GUI (graphical user interface) was for designers. Having to long press to create a knot and tapping to access its contextual menu — instead of relying on selection and global tool palettes — plus being able to explore and play with their own creative constraints, posed an additional challenge: It was not like in the tools they already knew. Yet, as soon as participants understood the basics, they were all able to express their ideas with *Knotation*. They suggested new possibilities, and most enjoyed the experience and were eager to continue using the tool in their creative practice.

Personalisation of creative constraints

As reported in the studies, participants appropriated *Knotation* in several ways. For example, they used portals to define relationships between dancers, trajectories as non-spatial concepts, timelines as grouping instruments, or as both spatial and temporal structures. By reifying temporal ordering and spatial configurations, participants were able not only to compose the time and space of the piece, but also to combine them into higher-level concepts that were as formal or as ambiguous as they wanted.

7.9.2 *Polymorphism*

Floorplans and timelines are polymorphic instruments. Floorplans accept as trajectories all semantic types of user strokes, including simple lines, drawings, symbols, text, and even timelines. In the current version, timelines accept any type of knot but only play video knots. Timelines could be made more polymorphic by also triggering the display of, for example, image knots or even floorplans and other timelines: Any object with a inherent or added temporal dimension should be able to be ordered and displayed in sequence.

The properties of knots attached to floorplans or timelines get automatically applied to all the objects on them — a behaviour inspired by the discussion in Section 5.10.2. For example, a speed knot on a timeline sets the playback speed for all the video knots on the timeline, which saves user actions. To exploit this behaviour, participants appropriated timelines as grouping mechanisms for related dance fragments before taking care of their temporal organisation, similar to designers with *StickyLines*. Also as with *StickyLines*, participants wanted to group timelines and floorplans and play them simultaneously. They wanted a *meta-instrument* capable of acting upon a set of instruments (polymorphically if they have different types) in order to achieve a goal. This is yet another example of the users' desire to treat instruments as objects of interest, and the power of polymorphism in this context.

7.9.3 *Reuse*

All the objects in *Knotation* can be cloned, and thus, reused, including users' sketches, knots, floorplans, timelines, and portals — a need discussed in Section 5.10.3 in the context of *StickyLines*. For example, the user can draw an inspirational symbol (such as the triangle in P6's project from Chapter 6), and clone it to reuse it as the border of a floorplan representing the shape of the stage, or as a trajectory inside a floorplan, or as a timeline.

In the structured observation, we observed that participants cloned their choreographic objects to reuse them in different contexts (for example, a pair of cloned spirals served as a spatial trajectory and as a timeline), or to reuse their properties (for example, to quickly create a set of floorplans with the same speed or duration but different trajectories, for different parts of a piece). Participants also appropriated portals to establish relationships and reuse their content: They defined a part of the piece only once inside a portal, and then cloned it several times and positioned the clones next to other dancers' knots or on timelines, to indicate when and where the common part had to be performed.

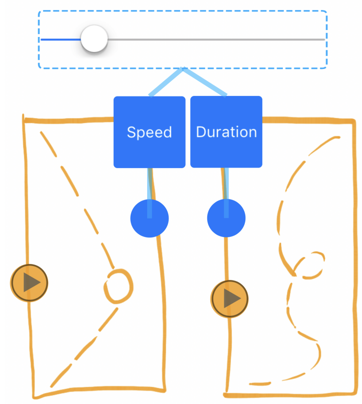

Figure 71: The same controller (slider) could be linked to several attributes (speed and duration) in different choreographic objects.

Given the principled design behind *Knotation*, reuse could be increased without much effort. Timelines could be pushed further by letting the user reshape them into, for example, circles or straight lines as in *StickyLines*, or into other custom shapes. As discussed in Section 5.10.3 in the context of graphic design, the interactive objects in *Knotation* could be made considerably more reusable by allowing users to *link* them to other objects, avoiding the need of cloning altogether. For example, the same slider could control a set of speed or duration knots in several floorplans or timelines, so that changes to this unique slider would automatically propagate to all the linked objects (Fig. 71). By extending the decoupling of constraints from content through linking rather than cloning, the user could define a minimal set of constraints, save it, load it, and quickly replace it for another set to explore their effect on content.

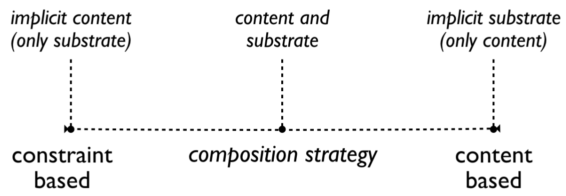

Figure 72: Continuum of composition strategies in relation with substrates: Constraint-based strategies make the substrate explicit but the content could be absent. Content-based strategies define the content while the substrate is implicit.

7.9.4 *Substrates*

In *Knotation*, the whole canvas with all the choreographic objects on it forms a substrate that operationalises the personal principles behind the composition of a dance piece. Both content and constraints are exposed so that the user can control, tweak, and appropriate them. On a smaller scale, a floorplan with its properties and trajectories is a substrate, because it embeds the user's principles about space, allowing the user to focus on the stage, on relationships between dancers and the stage and between each other, and on a particular dancer's movement. Similarly, a timeline with its properties and attached knots is a substrate that enforces the user's principles about time, enabling the user to focus on temporal and rhythmic patterns, without the need of fixing the space for the corresponding dance fragments. Users can combine floorplans, timelines, and portals to compose more complex substrates, as P5's in the structured observation. Supporting these spatial and temporal substrates and constraints in a way that matches how users actually compose a choreography, can make systems consistent, powerful, and it opens new possibilities for idea exploration.

Substrates and the continuum constraints–content

Substrates provide benefits along the continuum discussed in Section 7.9.1. Any point in between the extremes corresponds to a substrate where a set of constraints act upon the content, and the user can modify any of the two at will and check how do they affect each other (Fig. 72).

A constraint-based strategy is compatible with a substrate explicitly composed of user's constraints, in which the content is not necessarily present in a digital form at any point of the process. The users' objects of interest are the constraints themselves, and it is thus fundamental that they are reified, polymorphic, and reusable. In choreography, this corresponds to a way of composing a dance piece where the movements are generated or discovered by the dancers within the design space established by the constraints (as in P2's stories from the interview study in Chapter 6).

In the other extreme, a content-based strategy is the least compatible with the concept of substrates, or the one where the benefits of using such approach are the less obvious. This maps to composition strategies where the choreographer only documents movement content without leaving any explicit traces of the rules, constraints, structures, or high-level principles that shape it. In this case, the substrate exists in an implicit form coupled with the content, because any digital data has an inherent structure — for example, in a video, frames are ordered temporally. However, I believe that allowing the choreographer to store this content in an environment that allows the addition of constraints at any moment of the creative process, is more likely to open new paths than to restrict them.

Substrates in dance literature

The substrates approach is compatible with the *dynamical system* perspective proposed by Stevens et al. (2000) in the context of choreographic cognition, which includes relationships, propagation of constraints, and temporal and spatial dimensions:

> *"As the medium of contemporary dance is time we propose that the artistry of movement is in trajectories, transitions, and in the temporal and spatial configurations in which moves, limbs, bodies, relate to one another. Choreographic cognition can be conceived as a dynamical system wherein change to a single component can affect the entire interacting network of elements."*

Allowing users to define their own substrates can digitally augment these dynamical systems that are already present in choreographic cognition, and that choreographers already master, even if they do not always articulate them in these terms.

Stevens et al. also talked about the emergence and identification of structures and patterns, which is a fundamental aspect of substrates:

> *"In this theory [of dynamical systems] complex wholes and forms emerge from simple elements and in self-organising dynamical systems structures emerge from chaos. It is possible to apply the dynamical view to identify pulses, rhythms, patterns that spark an idea that is utterable in movement. The pulse or rhythm can occur in any modality but, for the creative choreographer, will be expressible as a composition of movement in space and time. Ultimately, we can apply the notion of dynamical systems*

> *to better understand, possibly to model, the movements and form of a single body, or many bodies, in space and time."*

The substrates approach explored in this thesis is not concerned with the modelling of movement, but with the expression of choreographic ideas in multiple modalities, and with the discovery and capture of movement patterns.

Interesting examples of substrates have been documented in the literature and could directly benefit from *Knotation*. Stevens et al. (2000) described a story where the dancers were to move forming a double-helix, during the development of the piece *Red Rain* by choreographer Anna Smith. The choreographer and the dancers had to perform a *"logistical analysis"* to define how the trajectories would unfold in space and time, considering the movements of each dancer and of the group as a whole. They used coloured paper trails to represent each dancer's path, and after visualising them with these concrete materials, they engaged in considerable trial and error to translate the model into real-time and space. In *Knotation*, this could be easily expressed by drawing the trajectories on a floorplan and animating it with different speeds to check where and when intersections would occur. Videos of key moments could be recorded and added to the floorplan over specific points in the trajectories, or organised along the border or on a timeline. Dancer knots could be attached to each trajectory to remember who does what. *Knotation* could be enhanced to allow choosing a colour for each dancer — to differentiate them or to mark subgroups. Of course, this would not replace the need of trying the sequence in real movement, but it would aid the experimentation while getting the documentation of the final solution at the same time.

At a more general level, the difference between content and structure, rules, or constraints has also been raised in the dance literature. Press and Warburton (2007) identified two perspectives of creativity in dance that emerged after World War II: Creativity as the design of external form and conventions of dance, and creativity as personal expression. Regarding the former, they mentioned an interview done by Martha Coleman (1949) to Louis Horst (Marta Graham's musical director), in which he emphasised the importance of *"structure"* over *"content"* in the creative process. He defined *"form"* as the *"application of traditionally accepted rules"* and stressed that creativity was based on the manipulation of these rules. For Horst, content was not the main attribute: *"If an artist has command of form, he need not be concerned so greatly with content"* (Coleman, 1949). By contrast, while for Horst the rules came from music, for choreographer Alwin Nikolais, another interviewee, *"dance should strive for its own forms"*, and the forms *"must serve to manifest the idea"*, which stems in the artist's perception (Coleman, 1950). I argue that a digital tool for choreographers that aims at supporting a variety of approaches to the exploration and documentation of ideas should recognise these two opposite views. It should enable users to reuse existing rules given by dance conventions, in order to grow content out of these moulds, as well as to generate or discover new ones, starting from a primal personal idea and building structure around it. The substrates approach employed in *Knotation* allows users not only to pick one of these strategies, but also to combine them.

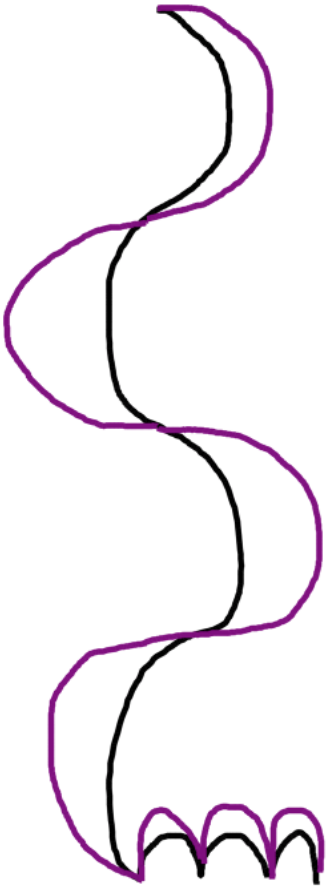

Figure 73: The actual sensed trajectory (purple) could be fed into *Knotation* and rendered over the designed trajectory (black).

7.10 PUSHING KNOTATION FURTHER

New forms of input to *Knotation* can be easily envisioned. PDF files could be imported, which would allow choreographers to incorporate their textual sources of inspiration. Handwritten annotations could then be extended to work over these files, as well as images and video. Another example involves exploiting the iPad Pro's support of multitouch: Dance makers could draw trajectories with all the fingers at the same time, or even collaboratively, encouraging a playful interaction.

Another interesting possibility is to detect dancers' trajectories and visualise the data in real-time (or close to real-time) in *Knotation*[20]. The actual trajectories could be overlapped and compared with the ones previously designed by the choreographer, in a different colour or line style, as in Fig. 73. The choreographer could choose which to keep and which to discard, or use them as a communication tool in feedback sessions. This would be the choreographic equivalent to *StickyLines*'s *tweaks*: Variations generated by dancers, which the system detects and persists, helping users make decisions or document the creative process. Moreover, the sensed trajectories could be the starting point for the choreographer to design the spatial patterns, based on dancers' improvisations. *Knotation* could provide a way to record alternatives for a

20 For example, a non-intrusive method would consist of placing a camera on the ceiling to record the dancers from above. The feed could be processed on a laptop computer that would send to *Knotation* the strokes to render, over a wireless connection using WiFi or Bluetooth. This simple setup would limit the detection to one dancer at a time, unless they can be distinguished from each other. Wearing only one colour of clothing each could help to simultaneously track several dancers. Markers such as those used in augmented reality are likely to present occlusion problems regardless of where in the body they are located, and dancers' comfort should be a priority over precision. Instead, the use of multiple cameras could be investigated in order to overcome occlusion. In any case, tracking a large number of dancers in real time would be a huge technical challenge. A more precise alternative is to use motion capture systems. This is not only more expensive and intrusive, but also harder to set up, which is a problem in the context of dance studios booked by the hour.

given dancer or trajectory. For example, a trajectory (or any hand-drawn choreographic object) could include an option in its *edit* menu (together with *clone* and *delete*) to *create a variation*. *Knotation* would then reduce the opacity of all the objects on screen so that the user can draw the variation without losing reference of the whole. Upon saving the variation, it would be stored in the original choreographic object. Proper methods should be designed to navigate, edit, and delete existing variations, or display them together.

Knotation could partner with the user to further explore content based on constraints. For example, a *mirroring* relationship could be implemented as a substrate in which the user draws a trajectory with the pen, while the system simultaneously produces a trajectory that mirrors the user's. Then, the mirrored trajectories can be manipulated to adjust their relative distance. *Knotation* could also make the *unison* relationship interactive. We can imagine the system playing trajectories completely in unison, completely sequentially, or with a certain temporal overlapping. A dedicated tool would not be necessary: Allowing the user to control an *order knot* with a slider (rather than the current binary switch) would suffice.

Layers could be provided to facilitate the dynamic organisation and visualisation of a *Knotation*'s document. For example, the user could create a background layer with the main floorplan of a sequence, plus a video layer that contains choreographic objects related to video (such as timelines and video knots). A third layer of handwritten annotations could be added on top, and shown or hidden on demand according to the user's context (documenting, revising, giving feedback, etc.).

Outside choreography, *Knotation* could be used in interaction design to create interactive storyboards before filming video prototypes. The designer could sketch a storyboard, including handwritten or typed notes, and include clips that illustrate the interaction. The clips could be then organised into a main timeline, or even several timelines that represent branching storylines. Inie and Dalsgaard (2017a) found that interaction designers use slide presentations to manage their ideas, perhaps because they can incorporate different type of media and documents, and easily move and reshape them. As this aspect of slideshow software resonates with *Knotation*, it would be interesting to study what would designers do if given access to the tool, and to what extent do design principles behind apply to their discipline. In addition, *Knotation* could also be explored in the context of other performing arts such as theatre, which involves capturing multimedia inspiration sources, text, spatial distribution of people and objects on a stage, interaction between performers and possibly with technology[21].

7.11 SUMMARY AND CONTRIBUTIONS

My goal was to design an interactive digital tool that supported exploration and documentation of choreographic ideas and constraints, without enforcing a particular creative process. Based on the conducted studies with contemporary choreographers and dancers, I designed and built *Knotation*, a mobile pen-based tool that offers a lightweight method for sketching choreographic objects with embedded images and video. Users can sketch their own personal representations of the dance, and add various forms of interaction to further explore their ideas, including creative constraints.

Using *Knotation v1* as a technology probe revealed contrasting strategies for capturing movement, constraints, or both. *Knotation v2* explicitly supports interactive timelines and floorplans, and incorporates participants' suggestions. I showed how *Knotation v2* supported opposite choreographic approaches (*dance-then-record* and *record-then-dance*), and allowed users a wide range of expression, at varying levels of formality.

I discussed how the principles of reification, polymorphism, and reuse, plus substrates support choreographers in defining and interacting with the content and the constraints in their compositions. The substrates approach illustrated in *Knotation* supports a range of user strategies, from completely based on constraints, to completely based on content, including strategies that start with constraints and develop content around them, strategies that adopt the opposite procedure, and mixed strategies where content and constraints are progressively defined as they affect each other. I concluded with directions to push *Knotation* further.

21 *Knotation* was used by a choreographer and actors in a 3-day workshop whose goal was to create an interactive theatre piece. A brief chronicle of this use case is described in the Appendix.

8 CHOREOGRAPHIC COLLABORATION IN THE WILD

This chapter explores the choreographic creative process when mediated by technology in real, collaborative settings. After reviewing the literature on collaboration in dance, it studies the relationships among choreographers and between choreographers and dancers in the context of using Knotation*. It then proposes a set of implications for the design of tools to support collaborative exploration and documentation of ideas in dance making.*

Dance making is an art form that rarely emerges in isolation and often requires time in a dance studio. Choreographers and dancers develop collaborative relationships on the base of each dance piece. Dancers can contribute with conceptual ideas, emotional qualities, concrete movements, or by solving choreographic problems. They can fulfil a variety of roles, acting as, for example, expressive *"instruments"*, inspiring muses, interpreters, full co-authors, or a combination. Dance researchers have studied these relationships primarily from the choreographer's perspective (see, for example, Morgenroth, 2004), whereas dancers' roles and experiences have been seldom acknowledged (Barbour, 2008; Barbour et al., 2016). While the collaboration between choreographers and music composers has been previously addressed (Mason, 2012; Rovan et al., 2001; Teck, 1989), relationships among choreographers have attracted little attention.

As discussed in Chapter 3, choreography is a form of distributed cognition in which choreographers and dancers share knowledge through dancers' bodies and memory, and artefacts such as video, diagrams, and scores. However, collaborative aspects of choreography and the potential for technological mediation remain underexplored. As put by Dalsgaard (2018), *"few digital tools [for creative work] are developed with collaboration in mind"*. Although some innovative technology has been designed to facilitate collaboration among content creators (e. g., Cabral et al, 2011; Singh et al., 2011), most focus on asynchronously annotating video artefacts, rather than early-stage creative collaboration.

The studies conducted in Chapter 7 did not go deep into the collaborative aspect of contemporary choreography. I thus ran two longitudinal field studies to capture ecologically valid collaborative practices and needs of choreographers and dancers. I was interested in studying the relationships among choreographers and between choreographers and dancers when they are mediated by a technology such as *Knotation*. The studies used the latest version of *Knotation* (described in Section 7.2), which included a number of improvements over *Knotation v2* to make it more robust for its use in the wild and in collaborative settings. Specifically, I made several optimisations in the rendering of drawn strokes, and implemented a more efficient use of AVPlayer instances for playing video[1]. I also added a feature to import content from other *Knotation*'s documents.

8.1 CONTEXT

COLLABORATION IN CREATIVE PRACTICES

Studies of collaboration in creative practices include Halpern et al.'s (2013) cultural probes with pairs of artists and scientists, Barbour's (2016) exploration of the value of collaborative relationships in art, and Salter and Wei's (2005) analysis of the collaborative nature of art practice in terms of shared language, construction of boundary objects, accommodation of differing cultures, as well as performance, materiality and agency. Within creative practices, choreography presents additional challenges because of the extreme diversity across choreographic approaches, and because dance is based on human movement, which is complex, multimodal, and hard to capture (Fdili Alaoui et al., 2015).

SOCIAL PERSPECTIVE OF COLLABORATION IN DANCE MAKING

Dance making relies on various types of relationships: Between a choreographer (normally directing the art making) and a dancer (typically embodying the art); between a choreographer and another choreographer (co-creating); and between a dancer and another dancer. These relationships are not exhaustive, as a dance production might also redefine the roles or define new ones, and thus new relationships among them.

Choreographer–Dancer relationship

Scholars in dance studies have addressed the roles taken by choreographers and dancers when working together. Blom and Chaplin (1982) mentioned Doris Humphrey as one of the first choreographers to consider the dancers' contributions, including their technical skills, personality, style, and creativity. In 2000, Bonnie Rowell analysed the status of contemporary dance in Europe and the UK, noting an emerging *"new way of looking at the dancer (...) whose agency within the dance statement is finally acknowledged"*

1 The AVFoundation framework limits the number of video players that can be assigned at the same time.

(Rowell, 2000). She vindicated the dancer's body as a site for political statement, in which nor the dancer or the body can be neutral. Rowell argued that implicit within this view is a new status for dance as a collaborative art. Similarly, Klien (2007) stated that in this new political context *"dancers are no longer* 'employed to perform'" and have to negotiate *"their personal freedom and subjective reality within a larger group"*.

Also in the context of UK's contemporary choreographic scene, Joyce Butterworth (2004) identified five *"processes of collaboration"* between choreographers and dancers: *Choreographer as expert and dancer as instrument; Choreographer as author and dancer as interpreter; Choreographer as pilot and dancer as contributor; Choreographer as facilitator and dancer as creator; Choreographer as collaborator and dancer as co-owner*. Butterworth proposed a framework called *Didactic-Democratic Spectrum* with three possible processes: dancers contribute to the choreographer's concept; dancers collaborate with the choreographer; and dancers and choreographers work together as an *ensemble*.

Looking at the post-Judson contemporary American scene, Sara Gibbons (2015) described the choreographer as a *"curator"* who *"selects, assembles, and sequences movement material, structures, and conceptual ideas"*. Gibbons talked about choreographers and dancers generating material together and inspiring each other, and noted that the responsibility emerges in the *"editing process"*, as guiding principles and questions evolve. Pamela Newell's (2007) Master thesis highlighted the dancers' perspective on choreographic collaboration, and identified different dancers' roles in the creative process, according to their level of agency: *executant, interpreter, participant, improviser*.

From a cognitive science perspective, Kirsh et al. (2009) conducted an ethnographic study with Wayne McGregor and the dancers from his company. They collected video, field notes, interviews, motion capture data, psychological tests, diaries, and notebooks. As a result, the authors elicited the methods used by the choreographer for creating dance with dancers: *showing*, *making-on*, and *tasking*. Each method presents different levels of agency and dancer creativity, and involves multiple communication modalities, such as the vocalisation of dance movements and rhythms.

All these works are indeed valuable to inform the design of tools to support choreography, as they remind us of the diverse and changing nature of the relationships between choreographers and dancers.

Choreographer–Choreographer relationship

Many dance companies include two or more choreographers, e. g., Emio Greco and Peter Scholten, or Peeping Tom. Other initiatives include collectives of artists, such as the *9 Evenings* events with John Cage, Lucinda Childs, Alex Hay, Deborah Hay, Steve Paxton, Yvonne Rainer, Robert Rauschenberg, David Tudor and Robert Whitman. These artists collaborated with 30 scientists and engineers from Bell Labs to develop and adapt interactive and reactive art (Oppenheimer, 2005). However, we are unaware of research that focuses explicitly on the relationship between choreographers in a co-creative environment.

TECHNOLOGICAL PERSPECTIVE OF COLLABORATION IN DANCE

Adding a new technology to any social organisation has an impact on the existing dynamics and practices (Joyce and Van de Ven, 1981). Although few technologies have been designed to support collaboration in dance, those that do deeply affect artistic collaboration patterns. Moreover, Latulipe et al. (2011c) examined six dance projects and showed that the effect on the creative process varies with the moment in which technology is introduced.

Collaboration between dance artists and technology

Over the past 40 years, technology has been created to collaborate with choreographers and dancers during the generation of movement material or during performance. For example, Carlson et al.'s (2015b) *iDanceForms* is a mobile sketching tool that partners with the choreographer to design creative movements *in situ*, but it has not been used to study collaboration between people in dance composition. Latulipe et al. (2008) designed several interactive dance performances involving dancers and projected visualisations, as well as musicians and improvisational methods, algorithms, and vision-based techniques (Latulipe et al., 2011b). Gonzalez, Cherry and Latulipe (2012) also contributed with specific design principles for building interactive dance: *connected kinetics, augmented expression, aesthetic harmony, interactive build, and integrated process*. In addition, based on their experience with the *Dance.Draw* project, Latulipe et al. (2011a) proposed an evaluation method for longitudinal projects that combine dance and technology.

Although these works are relevant for my goal, I was also interested in studying and supporting the collaboration between dance artists from the early stages of the creative process, beyond their relationship with performance technology.

Collaboration among dance artists through technology

Technology can also offer a medium for collaboration among dance artists. Yang et al. (2006) built a collaborative system for remote dancers to perform in a tele-immersive environment. Popat (2013) analysed how internet technology can support remote, collaborative choreographic creation as well as collaboration between dancers and the audience. Other tools focus on annotating video artefacts, such as the *Creation-Tool* (Cabral et al., 2011), and the *Choreographer's Notebook* (Singh et al., 2011), both already described in Chapter 7. Cherry et al. (2012) examined the socio-technical effects of introducing the *ChoNo* in the dance production process. Although designed for use outside of a dance studio, the choreographer decided to project the content of his *ChoNo* during rehearsals, so that he could go through the annotated videos in detail with the dancers. I was influenced by this observation, and I was also interested in analysing how choreographers collaborate among themselves.

8.2 FIELD STUDY WITH A CHOREOGRAPHER AND DANCERS

I was interested in the collaboration between choreographers and dancers when creating a piece, from the very beginning of the process to the final performance. My goal was to obtain insights that would inform the design of collaborative tools for dance making. But in order to grasp the subtleties of such collaborative activity and its development over time, I had to study the process outside of controlled laboratory settings, in a real-world scenario.

I thus observed a course on *Dance and Technology* at a local dance conservatory, given by Sarah Fdili Alaoui. The course was optional for the conservatory students and it did not involve grading. It was divided in two parts: Part 1 consisted of a 3-hour class per month during five months, and Part 2 spanned across five days, four hours per day. Students could enrol to only the first part, or to both. During Part 1, dancers would learn theoretical aspects of choreography such as Laban efforts and qualities (von Laban and Ullmann, 1948), and put them in practice by working in groups to compose choreographic fragments. During Part 2, dancers had to collectively create a choreographic piece to perform at the conservatory's end of the year show. The piece was to include diverse technologies such as interactive visuals, vibration sensors, and live electronic music.

Fourteen dancers enrolled to Part 1. Six dancers also enrolled to Part 2, so I focus on them in the analysis. Concerned about the dancers' work load, we designed the study accordingly: The debriefing and interview time were kept minimal and within the hours in which the students are normally in the conservatory. Naturally, participating in the study was not required for taking the course.

Participants: The choreographer in charge of the course (8 years of experience) participated in the study. A total of six dancers (five women, one man; ages: 19-32) followed both parts of the course and performed in the final show. They had between 5 and 16 years of dance practice (median: 14.5). Four had some experience with choreography creation (one for ten years, and the rest for three years or less), and two of these had also taught dance before (4 and 8 years). From the six, two wanted to become professional choreographers, and two plan to be professional dancers.

Hardware and software: The study used *Knotation v3* running on 12.9″ iPad Pro™ devices with iOS 11, and Apple Pencils™ for input. As *Knotation v2*, *v3* is implemented in Swift 3, manages video through Apple's frameworks AVKit and AVFoundation, and uses two ad-hoc gesture recognisers for drawing with the pen (by panning) and for creating knots or invoke their editing menus (by long pressing). *Knotation v3* includes all the features described in Section 7.2, except for the definition of speed or duration knots at the trajectory level.

Setup: Before the official start of the course, the choreographer organised a meeting with the dancers at the conservatory, where she described the learning objectives and the available technologies. I introduced the goals of the study, and gave a demonstration of *Knotation*. Dancers had time until the next session to decide whether they wanted to participate in the study. Each class was held in the dance studio assigned to the course. While in there, dancers could use the iPads at any moment and as much as they wanted. However, they did not have access to the devices in between classes. To minimise the chances that the dancers felt observed, I was the only non-dancer present in the studio.

Procedure:

Part 1: The first class of Part 1 (which I abbreviate P1C1), dancers read and signed the informed consent. The choreographer asked them to divide in groups of three or four people. I gave one iPad and one pencil to each group, and trained them in the use of *Knotation*. I also gave an iPad and a pencil to the choreographer. Then, each class, dancers followed the choreographer's instructions while I observed. Towards the end of each class, I asked the dancers to explain what they had created in *Knotation*, if anything.

Part 2: During the intensive week, as instructed by the choreographer, dancers stopped working in groups and divided into pairs. Each pair was to compose their own choreographic fragment (a duo). Then they integrated these fragments into the global structure of the piece and learnt some sequences that they would all perform together. In the middle of the week (P2C3), I interviewed each dancer for approximately 10 minutes, using a variation of the critical incident technique (Mackay, 2002) (Section 1.2.1). I asked them to tell me about recent, memorable stories of collaboration with other dancers and with the choreographer, as well as stories related to the available technologies (Kinect, vibration sensors, *Knotation*). I focused on both rewarding and frustrating moments.

Data collection: I placed a camera on a corner of the studio to record video and audio, and I took notes. I limited the number of pictures and close-up videos to avoid distracting the participants. I logged their interaction with the iPads, and I filmed the interviews avoiding participants' faces.

Data analysis: I translated the raw data to English, as all participants spoke in French. With one of my advisors, we used a thematic analysis (Braun and Clarke, 2006) approach to code the data (Section 1.2.2). We focused on the collaboration among dancers and with the choreographer, seeking to capture inspiring practices and needs, as well as breakdowns and bright points. We based the analysis on interview transcripts and notes from the observations.

8.3 RESULTS AND DISCUSSION

I report how the social dynamics changed during the course, how they shaped *Knotation*'s patterns of use, and in turn, how the introduction of *Knotation* affected the social dynamics and the creative process.

SOCIAL DYNAMICS

Dancers perceived a tension between their agency and the choreographer's hierarchical role

The dancers expressed the challenge of balancing their own agency knowing that the choreographer would have the last word. For example, P4 explained: *"She [the choreographer] gave us the chance to create and at the same time she had a very particular idea in her head. So maybe that was hard to manage because on the one hand she would tell us* 'yes, go on, it's yours, it's your material'*, and then no..."*. The choreographer explained the reason behind this tension: *"Because they lost the focus I was like: Ok, I'm taking this in charge. I'm making the whole score (...) In dance, there always should be someone who says: that works, that doesn't. Being in charge also takes some agency from them"*.

The choreographer also reflected on a component of trust that needs to complement the choreographers' hierarchical role for the collaboration to be successful: *"There's something about collaboration: Sometimes you have an idea, but in order to get to it, there are so many steps you need to explore, and the dancers don't know that idea you want to get to, but they have to trust you"*.

Dancers' membership feeling increased their level of engagement with the piece

A feeling of belonging to a group and being part of the creative process developed during the course. In Part 2, dancers started showing more solidarity among each other, for example, by teaching phrases and helping others master certain movements (Fig. 74a). Although they worked in pairs[2], the interaction across groups increased considerably, unlike Part 1, when the groups tended to work in a more isolated way.

The choreographer noticed a change in their attitude in P2C3, after she presented the *"global structure of the piece"* and they had the chance to play with the vibration sensors and the Kinect's visualisations: *"For me there was a difference today in terms of their engagement with the piece (...) I guess maybe today they started seeing where it was going... They started to think the piece might look good"*. That day, P5 referred to the choreographer's diagrams in *Knotation*: *"Having her [the choreographer's] visualisation was good to orient ourselves in the totality of the piece... And I really liked when we worked to fix the little things, to ensure they make sense as a whole... All the common work... I think it's from here that it became interesting"*. Similarly, P4 said at the end of that class: *"I think we arrived to a moment where the structure is very clear, we know what we have to do, and this allows us to find more links, to find meaning in our actions in the chaining of things"*.

After P2C3, the choreographer took progressively fewer notes, relying on the sense of membership that was generated among her and the dancers. She said she trusted in their responsibility to remember the decisions made as a group: *"In dance you're relying on people and they rely on you"*.

When dancers' engagement increased, their suggestions became negotiations

In Part 1 there was no interaction across groups, they were all working on their own compositions, discussing among themselves and occasionally asking for feedback from the choreographer. At the beginning of Part 2, a few dancers started making individual suggestions to the choreographer, which she would

2 P2 worked with P3, P4 with P5, and P1 (initially paired with P6) with P2.

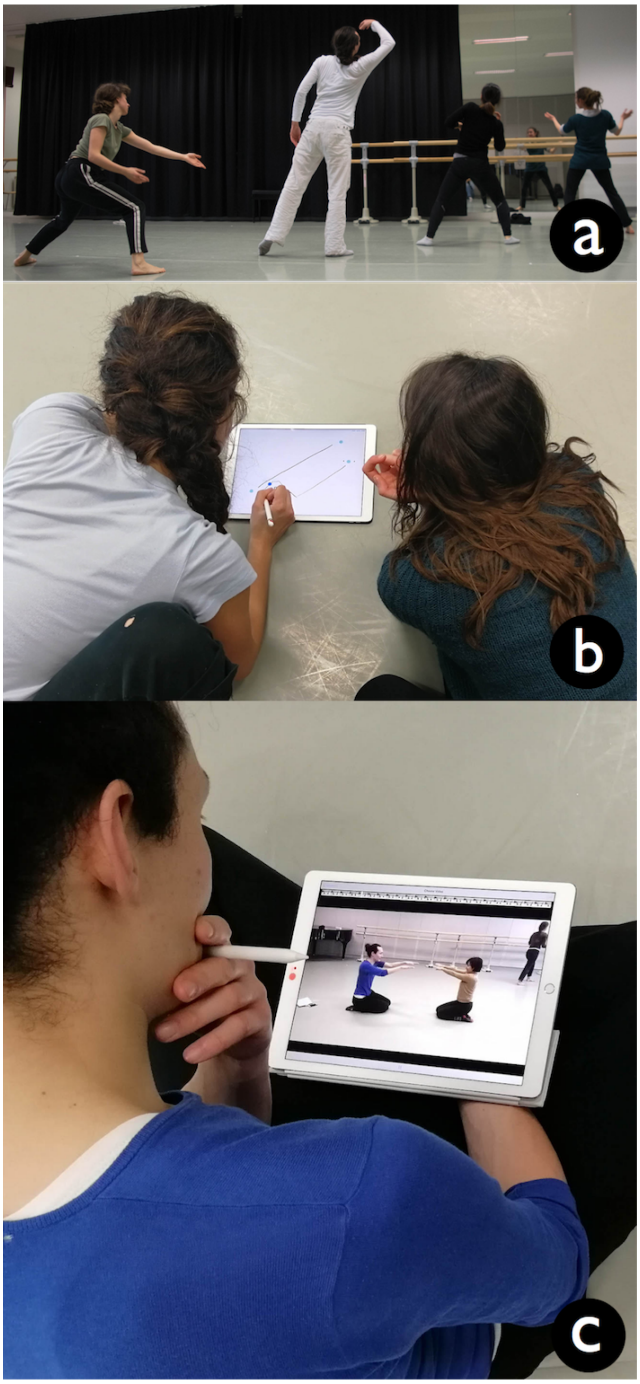

Figure 74: Course: Dancers rehearse a common phrase in Part 2 (a). Dancers draw spatial trajectories in *Knotation* to document their duo (b). A dancer revises a video of a dance sequence to examine details (c).

either accept or reject. However, as the course progressed, this exchange developed into a more active discussion where they would negotiate choreographic aspects.

SOCIAL DYNAMICS SHAPING KNOTATION'S USE

The choreographer's hierarchical role determined Knotation's patterns of use

In Part 1, the choreographer used her hierarchical role to set a common work dynamics. She would often ask each group to show their fragments to the others, otherwise they would work isolated from the rest. P5 explained: *"The fact that we [with P4] used the iPad at the end of the session... it was a bit like homework (...) It was ok because it forces you to make a memory effort, so that's reworking the thing in a different way..."*. Perceiving the interaction as homework was already reported by Cherry et al. (2012) in the context of dancers using the *Choreographer's Notebook*. Moreover, Latulipe (2013) reflected on the trade-off implied in the use of the *ChoNo*: While it provided dance artists with rich exploration and communication of their work, it also had a cost for users in terms of their work-life balance.

In Part 2, dancers incorporated the annotation practices to the process by their own initiative (Fig. 74b). The choreographer used *Knotation* from P2C3 on, when she created a *"global score"* and added each duo's score into it. She decided that the dancers would stop updating their compositions on their iPads, as it was her who would centralise the global score on one device. From that moment on, her annotations in *Knotation* implicitly became the one source of truth in terms of score, and constituted a shared object (and place) to which the dancers would spontaneously come and sit around on the floor.

Participants used Knotation to mediate negotiations

During the last three classes, participants would all sit on the floor around the iPad at least once per class, in order to watch the videos they had shot for each part of the piece. The choreographer would play the videos in *Knotation*, pausing them often to point at the details she wanted to highlight. She would perform mid-air gestures and mark movements to indicate corrections, proposals, and aspects she liked. The dancers would detect eventual mistakes and make their own suggestions. P4 referred to the negotiation with the choreographer in this context: *"We compromised. She accepted things, we accepted things. We saw what works and what doesn't. (...) The videos helped a lot"*.

Dancers' technological resistance affected their use of Knotation

Several dancers referred to their reticence for digital tools, which affected the way they used *Knotation*. P1 said: *"One can feel that it [Knotation] can be very powerful (...) But we have all some sort of laziness that makes us write [on it] as we are used to"*. P2 expressed her reluctance towards tablet applications: *"I have a lot of trouble with iPads, but that's me, my nature, I never use this type of thing, I'm not at ease with it... I prefer writing. It doesn't help me, [the fact of] doing portals, doing scores..."*. Along the same lines, P5 said: *"I have this reticence for digital tools, a bit silly, I have the impression that we have too many"*.

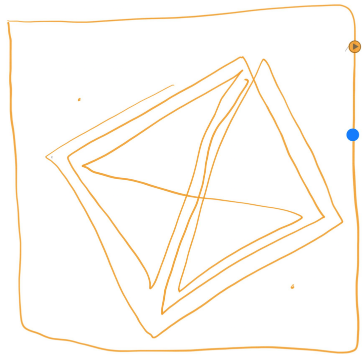

Figure 75: Course: The choreographer explored the dynamics of the trajectories on a floorplan representing the *"the walk"* dance sequence.

With Knotation, dancers documented, the choreographer explored

Dancers worked in a highly embodied way during the exploration of movement variations: They would try alternatives with the body first and then use *Knotation* to annotate only the final choices. P3 stated: *"I think it's a novel way of preserving a document, where we can write down more things than with video"*. P1, however, used the technology not only to document but also to revise choreographic material: He recorded movements in slow motion, imported them into *Knotation* and played the videos to check interesting details (Fig. 74c). By contrast, P4 explained why she and P5 did not use interactive features such as floorplans and timelines: *"We didn't really have the need... We used the iPad as a digital notebook"*.

The choreographer used *Knotation* in a more exploratory way, to spark choreographic ideas. For example, she showed me a floorplan for a dance sequence she called *"the walk"* (Fig. 75): *"This is where Knotation is interesting, because I was able to do this, and I think I couldn't have done it (...) if I was to do it on paper... Because I was able to play it and I saw: Oh, this is creating a nice pattern! And I was able to try it with the dancers"*. However, she also mentioned the lack of time to try different alternatives in *Knotation*: *"If I were in my own studio and I had two weeks of rehearsals I could do multiple of these and try them out. (...) But here I have only four hours per afternoon for a week, so I'm like: Here, these structures, take them and then go to the next thing"*.

Figure 76: Course: The choreographer and the dancers represented and discussed dancers' trajectories by moving their fingers on the floor.

Another story of exploration mediated by *Knotation* involves the choreographer and two students discussing possibilities for a transition. They placed their fingers vertically on the floor to indicate dancers' initial positions, and moved them at different speeds to indicate the trajectories (Fig. 76). The choreographer proposed to continue in *Knotation*, so she created a floorplan illustrating her idea and played it. As they discussed alternatives, she deleted the trajectories. Then the students drew their own trajectories in turn, to communicate their proposals, and played the floorplans. Each time they would suggest a new configuration, they would delete their previous trajectories. At the end, the choreographer redrew only the one she chose, in order to document it. Although they could have kept all the alternatives in *Knotation*, they didn't: *"I wanted to quickly discard ideas to try fewer physically. (...) I wanted to delete, try again, just sketch... but I didn't want the thing to exist anymore after that"* (the choreographer).

Hierarchical roles affected technology-mediated transmission of choreographic material

In Part 1, the choreographer worked exclusively with a paper notebook as the external support for the choreographic material she created. She transmitted it by showing her annotations (mostly diagrams and text), but also by talking, gesturing, and marking movements. The dancers simply asked questions to check they understood.

In Part 2, the choreographer used *Knotation* extensively during the last three classes to create and then transmit the global structure. One dancer appreciated that she had included floorplans: *"Normally the directions on the diagonal would be a nightmare for me. It was really great that you were able to prepare it in advance, that you did it on the iPad. It would have taken me [a long time]. (...) I think most of my problems with directions were solved because of what you did. (...) It's great"* (P1). The choreographer also conducted feedback sessions around the rehearsal videos that she incorporated to her score each day, indicating corrections and things she liked.

Dancers used *Knotation* in a more horizontal way, to transmit their compositions to the other members of their group whenever one of them wrote something alone, or when a dancer missed a class. When P1 was reassigned with P2 for the duos, P2 had to learn new material from scratch. P1 talked about the experience of using *Knotation* to transmit the phrases: *"I changed partners several times. (...) The videos allowed me to transmit quickly. First I showed a scheme to [P2], then the chain of videos too, then the animated chain, to see how the two people advanced... And that went very fast. We can consider that Knotation fully fulfilled the job because I used the score for [P2] and she didn't know anything about the score, and she understood everything"*. P2 also referred to this story from her own perspective: *"[P1] placed the iPad and told me* 'I let you to it', *and I succeeded at understanding what [P1] had done"*. However, she added: *"It helped me to have a first vision of the duo, but it required [P1]'s explanation. If [P1] hadn't been there, if I had had only the iPad, I think I wouldn't have succeeded at understanding everything. In fact it's the videos that helped me"*.

KNOTATION'S USE SHAPING THE SOCIAL DYNAMICS AND THE CREATIVE PROCESS

Using *Knotation* had an impact on one dancer at the personal level: *"I actually don't like to look at myself... But with this tool I also accepted it better"* (P1). The introduction of technology also had an effect on the relationships between the choreographer and the dancers, which I report below.

Dancers agreed on a common writing policy when their personal styles conflicted

In both parts, dancers had to share one iPad with their group. Some groups used the pen in turns without much planning, while others decided to agree on a common policy for their annotations. In particular, P2 said that in her group they all had *"different writing methods"* (for example, one liked timelines, but another preferred text), so their solution was *"to simply chose one"*. They selected P3's style, and maintained this role assignment for the rest of the course.

Interestingly, dancers did not include the choreographer into their writing negotiations. In fact, the choreographer found a breakdown in the collaboration, when she could not understand some groups' scores: *"That's the thing about collaboration, how do I understand what you're writing? Especially if you're writing it in your own style"*.

Dancers reflected on how to notate dance in relation with the available technologies

Confronted with the task of documenting their work, dancers considered how to write their choreographic phrases, often relative to the available technology. For example, P3 said that *Knotation* made her reflect on how to notate dance, since *"video is not enough"* to *"detail movement"*. She mentioned aspects of their composition that could not be captured through video, for example, movement intention or metaphorical images such as *"soaking"*. She added: *"We write it but I have the impression that with the iPad we could do it in another way. (...) It would require doing something three-dimensional to see how a movement deconstructs little by little, very slowly, because sometimes the video goes too fast. (...) The video also needs to be well shot, but then the fact that we can cut it is great"*. P5 had a similar view: *"So you can take videos... But I think that doesn't use the interesting part of it [Knotation]. (...) I think that drawings allow visualising movement better than video"*.

In some cases, interacting with a feature in *Knotation* made dancers try to articulate concrete dance concepts. For example, after learning to use floorplans, P2 and P3 said that they were trying to understand what it means for them a trajectory in space and thought about how to better represent its qualities, such as *"being irregular"*.

Dancers used technological and non-technological methods to learn dance phrases

Dancers used *Knotation* as a reminder for themselves at the beginning of each class. Most groups often came back to their iPads on the floor during the class to check some detail or write something down. P4 explained: *"It's like a trace. We used [Knotation] as traces"*. P1 reflected on the value of having the sequences filmed from class to class: *"A very happy moment, because it allowed me to progress faster, to unblock the memory also, was having the videos, of course... Because it comes back instantly [to our mind] once we have them"*.

Floorplans helped P1 to learn a specific choreographic aspect: *"I have a lot problems with space, so the fact of having a diamond on the squared room, it would have been harder for me to understand, it's not ultra dynamic to my eyes on a notebook. So that I think that's really an added value [of Knotation] (...) and the fact that it's interactive and progressive. (...) The fact of being able to see it several times without bothering anyone, replay it, and see the traces in space as someone that advances... The memory of images is one thing, and the memory of visualised movements, it's completely another thing"*. P1 also referred to the importance of interactivity in this context: *"Video, accumulating media, is good, but... What is really good is the interactivity, or reality, well, not augmented, but... things we couldn't do by hand... It's like if the paper was alive... Seeing a pencil that draws like Harry Potter"*.

Dancers also vocalised dance sequences in a consistent way, in order to learn them. P4 and P5 defined a sound for each part of a complex trajectory, and would *"sing it"* when performing it, until they learnt the sequence. Later, this practice was extended to all the dancers; for example, they all vocalised a jump in order to cue each other and synchronise.

The integration of the available technologies increased the dancers' engagement with the piece

In P2C3, the choreographer integrated the Kinect's visualisations and the vibration sensors into the working environment. For example, she asked a dancer to record some feet movements, such as tap and slide, next to the vibration sensors. They would later use the recordings to train a machine learning algorithm to recognise the different types of sounds. The Kinect application[3] displayed abstract visualisations that augmented body silhouettes. The visualisations responded to dancers movement speed with different textures and colours (Fig. 77). The dancers spontaneously started improvising movements to see the effect on the visualisations. Quickly, a co-adaptive behaviour unfolded (Mackay, 1990): They appropriated the system by dancing together and tricking it into detecting them as only one blob; and they adapted their behaviour according to the feedback they got from the system, changing not only their speed but other movement characteristics such as the size and the rhythm. The choreographer said that the Kinect's sensor would constrain the space, so she asked them to perform closer to it and adapt their positions to the sensing range. The same day, the choreographer used her global score in *Knotation* to transmit the global structure of the piece.

Figure 77: Course: Participants experiment with the Kinect's visualisations.

Dancers referred positively about this class: *"It's true that in the first rehearsal it was too abstract for us because we were going through many things... For the final production we didn't see the need for digital tools but then the sensors and the visuals instantly contributed with interesting material"* (P3). P4 reflected on how technology affected the creative process: *"As we work with these novel technologies, they have an impact in the way we work. It's true that we could have worked without them, but we would have worked in a different way"*. The choreographer agreed: *"The additional technology isn't only augmenting the stage but also bringing in different ways to see the choreography, different entry points. And it completely influences how the material is created"*.

TECHNOLOGICAL NEEDS AND OPPORTUNITIES FOR DESIGN

Using *Knotation* in this field study also helped me identify limitations of existing features, missing features, opportunities for design, and observe how users combined the power of *Knotation* with that of the iPad. For example, P3 had trouble with setting the order of trajectories on a floorplan, since *Knotation* did not offer a way to change it once the trajectories were inside. She also would have liked that the media knots over each trajectory get triggered when the animated line passes through them. The choreographer needed to define subgroups of trajectories inside floorplans and assign *order* knots to each group, so that some would be simultaneous and some sequential.

Dancers collaboratively assigned sounds to movement qualities or transitions in dance phrases. This could be incorporated to *Knotation* by adding a *quick audio recording* feature accessible from

3 Developed by another student from my research lab for a different set of projects.

any type of knot. In this way, users could add a recorded sound to a *tag* knot that indicates a transition and put the knot on a trajectory. Then, when playing the floorplan, the sound would be triggered at the right moment. This could help users memorise the phrase, or even be able to dance it while the floorplan plays, receiving audio cues at the key moments without having to be close to the iPad.

Participants combined *Knotation* with the power of the iPads for sharing content among them and for video editing. For example, P3 wanted to get a video from P4's iPad, so they quickly used *AirDrop*™ to transfer it. P3 wanted to cut short clips from a long video, so she did it with *iMovie*™. At some point, the choreographer and the dancers discussed whether it was better to record a long video and cut it in iMovie, or a series of short clips. They went for short videos to avoid the editing task, since they could simply concatenate them on a timeline in *Knotation*.

Overall, this study showed that the features in *Knotation* are not limited to choreographers: They can be used by dancers and are relevant for them in collaborative settings. However, some dancers prioritise bodily movement exploration and prefer to use a tool such as *Knotation* only to document the final choices. Even in this case, some perceive the notation activity as homework — possibly influenced to some extent by their reluctance towards digital tools, or because they were actually taking a course. On the other hand, this was the first time that some of the dancers had to produce a score for a piece. As they had never experienced the need of revisiting the documentation of a past project, they did not have the same expectations as the choreographer about keeping interactive representations of their ideas. Our results suggest that from the dancers' perspective, the potential of a tool such as *Knotation* in this type of collaborative classroom environment might reside in the documentation and transmission of choreographic material (horizontally or vertically), and in aiding to solve learning problems. However, individual differences in this context are considerable and dictate how users relate to the technology (individually and as a group), which must be flexible enough to accommodate this diversity of needs and expectations.

8.4 SUMMARY

In this study, I followed a choreography course with a choreographer and six students, over five months. Results show that dancers perceived a tension between their own agency and the choreographer's hierarchical role, and tried to find a balance between following instructions and defining their own space for creation. As the course progressed, a growing feeling of membership and responsibility increased the dancers' engagement, and the relationship with the choreographer evolved from simply suggesting ideas to her, to discussing and negotiating choreographic proposals in a more horizontal hierarchy. Of course, the initial vertical nature in this collaboration might have been strongly influenced by the setting being a classroom, as the relationship teacher-student in a formal institution is inherently hierarchical.

I introduced *Knotation* in the first class. I observed how the social dynamics between the choreographer and the dancers deeply influenced their use of *Knotation*. Once the choreographer started creating the global score and incorporated the dancers' annotations, the choreographer's became the one source of truth and a shared object around which they would all gather. There was a component of technological resistance, perhaps coupled with the limitation of existing features, and a prioritisation of embodiment, that made most dancers use *Knotation* to document and transmit their compositions, rather than to explore movement ideas. By contrast, the choreographer extensively played with her interactive objects to discover new possibilities. Hierarchical roles were also reflected in how and why participants transmitted their choreographic material with *Knotation*: While the dancers did so to teach each other, the choreographer used it to explain the global structure and to conduct feedback sessions, marking corrections and aspects to fix.

In turn, the introduction of *Knotation* affected the creative process and the relationships among collaborators. It provoked reflection on what to notate and how. Some dancers agreed on a common writing method before using the iPad, to compensate for conflicting styles. Dancers used *Knotation* to learn dance phrases, for example by interacting with timelines and floorplans, and playing with different video speeds to see details. For some dancers, the use of a new tool for exploring and documenting their compositions at the beginning of the process felt "*too abstract*" and they saw it as doing "*homework*". However, in some cases, their perspective changed once the choreographer presented the global structure and integrated the available technologies, and the dancers got more enthusiastic and engaged. Interestingly, the choreographer documented less and less as the dancers' engagement increased, trusting in their responsibility regarding the progress of the piece. At the personal level, using video to capture phrases helped one dancer to get used to see himself recorded, and visualising floorplans in *Knotation* helped him with his "*spatial problems*".

8.5 FIELD STUDY WITH A DANCE COMPANY

The previous study did not include more than one choreographer collaborating to create a piece together. As I was interested in studying the relationships among choreographers, as well as the dancers' perspective and expectations in this context, I ran another study. I observed a 3-day residency of a dance company working on an interactive dance piece. The piece involved an active audience that interacted with four dancers on a shared stage, following instructions on their smartphones. At the time of running this study, the piece had already been performed before, but the choreographic material was being adapted to a new venue, and it was not fully documented.

Participants: Six professional dance practitioners participated in the study. The project was directed by two choreographers (years of experience: C1, 8, C2: 35). C1 was one of my advisors, and C2 was a participant in the technology probe study from Chapter 7. The other participants worked as dancers in the company (two women, two men; ages: 30-44). The dancers had between 23 and 34 years of dance practice (median: 27). They all had experience with professional choreography creation (one for 20 years, one for 10, and the rest for less than one year).

Hardware and software: The study used *Knotation v3* on 12.9" iPad Pro™ devices with iOS 11, and Apple Pencils™ for input. After the second day of observation, I added a feature by participants' request: controlling the speed or the duration of one trajectory on a floorplan independently from the others, by attaching a speed or duration knot to the trajectory.

Setup: The 3-day residency was held in the theatre where the piece was to be presented. Since the choreographers and the dancers had a very tight schedule, we designed the study so that I would interview them during empty moments in between their planned activities. To avoid that the participants felt too observed, I was the only non-dancer present during the three sessions, including lunch breaks. While in the theatre, participants could use the iPads at any moment and as much as they wanted.

Procedure: The choreographers decided with the dancers at what time they would start and finish each work day (mean duration: 8 hours). In Session 1, participants read and signed the informed consents. I gave a demonstration of *Knotation*'s use and was available for questions along the whole study. In Session 3, I interviewed each participant for approximately 10 minutes, using a variation of the critical incident technique (Mackay, 2002) (Section 1.2.1). I asked participants to tell me recent stories of collaboration with the other participants, as well as frustrating and rewarding moments in relation to the technology (e. g., the iPad's camera, *AirDrop*™, *Knotation*'s features, etc.).

Data collection: I placed a camera on a corner of the studio to record video and audio, and I took notes. I limited the number of pictures and close-up videos to avoid distracting the participants. I logged their interaction with the iPads, and I filmed the interviews avoiding participants' faces.

Data analysis: I first translated all the raw data to English, as some participants spoke in French and some in Spanish. With one of my advisors, we conducted a thematic analysis (Braun and Clarke, 2006) approach to code the data. We put the emphasis on the relationship between the choreographers, and on the dancers' relationship with them and among each other. We looked for interesting collaboration and annotation practices, technological needs and breakdowns, and surprises. We focused on interview transcripts and notes from the observations.

8.6 RESULTS AND DISCUSSION

At the beginning of Session 1, the choreographers and the dancers warmed up and agreed on rehearsing the piece part by part, while filming it. In between parts the choreographers would conduct a short feedback session. Each time, the choreographers indicated corrections and highlighted what worked well, and the dancers expressed what they felt, proposed specific changes, and they all discussed alternatives. In the afternoon, the choreographers proposed to use *Knotation* to start notating the piece. I explained *Knotation*'s features and the participants played with it for a few minutes. Then the choreographers took an iPad each and asked the dancers to work in pairs. P1 and P4 worked together, P2 worked with P3, but also with C2. To finish the work day, they invited me and the actors from the theatre to participate as the audience, and they performed the piece. Then, they asked the members of the audience for feedback.

In Session 2, after the warm-up session, participants continued notating the piece, from the morning until the lunch break. In the afternoon, C2 proposed to film close-up videos for capturing small gestures and body parts' positions in specific dance phrases.

In Session 3, participants warmed up and had a long feedback session while watching on C2's laptop a series of videos they had taken the previous week. The dancers took notes on their paper notebooks. After that, C1 proposed dancers to finish their scores in *Knotation*. They ended the day with another rehearsal in front of an audience from the theatre, and a round of feedback with them.

The next day, after the residency finished, participants gathered again. C2 brought a book with artwork that they had used at the very beginning of the creative process as an inspiration for the *"sculptures"*. These were key moments in the piece where the dancers would crystallise certain postures for several seconds. They had changed them in such a way that they did not remember which were the original images. They photographed the relevant book pages and imported them into the score in *Knotation*. This allowed them to rediscover and discuss details, such as the position of the feet and hands. According to C1, they would not have engaged in this reflective activity without *Knotation*: *"It played the role of a memory that was somehow lost"*[4].

SOCIAL DYNAMICS BEFORE THE INTRODUCTION OF KNOTATION

Dancers did not perceive collaboration problems with other dancers, nor choreographers between themselves

When I interviewed the dancers about frustrating moments in the collaboration with other dancers, none of them recalled any incident. Similarly, the choreographers did not express any frustration about their own collaboration. Both of them mentioned having differing artistic visions at the very beginning of the project. Yet, they saw it as a part of the collaboration process, and highlighted how easily they were able to reach an agreement and set common goals, by discussing openly their ideas and respecting each others' roles and expertise.

Dancers needed a more clear hierarchical structure with respect to the choreographers

The choreographers recognised the dancers' expertise not only as performers but also as choreographers. The dancers, in turn, were very involved in the generation of choreographic material and its integration into the global structure of the piece. This resulted in a much more horizontal hierarchy than the one I observed in the previous study.

Interestingly, two of the four dancers would have preferred that the choreographers took in charge a range of decisions, such as defining the series of activities for each session and supervising their pace. For example, P3 said: *"There's a stretching of time where no one really takes the initiative of starting to do some work or propose something, and sometimes that bothers me a bit"*. P4 found it harder to respond to two choreographers, although he perceived

4 Personal communication after the end of the study. Paris, 2018.

the relationship between them and with the dancers as *"very horizontal"* and *"very respectful"*: *"The fact of having two choreographers can be an advantage and a disadvantage. Because they collaborate but they can have differences"*. He also referred to the dancers as being in the *"inside"* and the choreographers on the *"outside"*: *"So from the inside, I don't feel there's one head, there are two and that dilutes the work, personally I prefer working with one person in charge of the project and someone who collaborates with this person"*. He would have preferred that they made the decisions: *"Because we don't have that external vision that it's very important, we're inside the project..."*. Similarly, P3 noted that the choreographers are *"pretty horizontal"* between them and with respect to the dancers, but also referred to *"sides"*: *"I like the idea that there's someone who makes the decisions. Given my particular* parcour, *I spent 20 years with my own dance company doing what they're doing: making the decisions, even though it's done in a collective way too. So now here as a performer, I'm on the other side"*.

The transmission of choreographic material from dancer to dancer generated a feeling of membership

Before the introduction of *Knotation*, participants normally managed the distributed knowledge about the piece by asking each other questions. For P3, the sense of owning a phrase and transmitting it to the others favoured the horizontal communication between dancers: *"We didn't know each other when we started working, but a group emerged and we go together. As each choreographic phrase was created individually, and transmitted to the other dancers... Then [the choreographers] revised the material, but the proposal was ours. So having to transmit the material... There's a horizontal communication with your colleagues. That very horizontal communication... I like it very much when creating things, generating content, and it makes it all ours"*.

IMPACT OF KNOTATION ON THE SOCIAL DYNAMICS AND ON THE CREATIVE PROCESS

Participants reflected individually and collectively on how to notate dance

P3 appreciated having access to the others' scores to see if they captured a choreographic aspect he missed, and similarly, P2 referred to both individual and collective reflection processes during the sessions with *Knotation*: *"It's interesting to search... each one individually, and then with the whole group... See what each one found, how can a thing can be adapted... or that you didn't know* *how to write...".* P1, instead, was not interested at all in seeing the others' scores and wanted to reflect on the notation by herself: *"Because each one has its own and it's nicer to find it by ourselves"*. She said that using *Knotation* made her not only reflect on how to notate the dance but also want to explore different options: *"With this you search a bit more, as there's the possibility of drawing, erasing..."*. Interestingly, P4 said he would prefer having an assistant for handling the recording of the choreographic decisions and the score making, if he was to use a tool such as *Knotation*.

When transmitting content with Knotation, the hierarchical roles blurred

After the introduction of *Knotation*, participants incorporated video and their digital scores as ways of transmitting their creations. All participants shared with the rest the videos they filmed, right after capturing them. I did not observe vertical divisions between choreographers and dancers regarding the transmission of choreographic material when using *Knotation*, in contrast with the previous study. Moreover, C2 said that the introduction of *Knotation "changed the dynamics"*, as the dancers worked first in groups on their own scores but quickly started to check what the others were doing. He noted that they also started to share their documents spontaneously. C2 reflected that before *Knotation* there was a *"division between choreographers and dancers"*, where sometimes each group was *"in their own universe"*. He added that while the choreographers typically focus on revising, correcting, filming or watching the choreography, *"the dancers work at a very physical level"*, and that the introduction of *Knotation "made dancers go into a less physical time that was different"* and that made them *"involve themselves more in the writing of the choreography"*. For him, still, it was important that they could *"alternate these times"*, since dancers *"should avoid intellectualisation"* when working at a physical level. This resonates with Grove's (1999) observations during the development of the piece *Red Rain*. Grove noted that dancers intellectualised the exploration of movement when it was triggered by verbal cues. However, according to Grove, they also internalised the movement better, rather than *"relying on a picture or mirror-image of what the spectators see"*.

Each choreographer developed their own style of using Knotation

In Session 2, C2 tried a few ideas in *Knotation* and then collaborated with P2 to start documenting the phrases of each dancer. After agreeing in what they would notate, he filmed videos of her dance sequences (Fig. 78a), and then gave her the iPad and delegated the documentation task. C1, instead, wanted to get the final

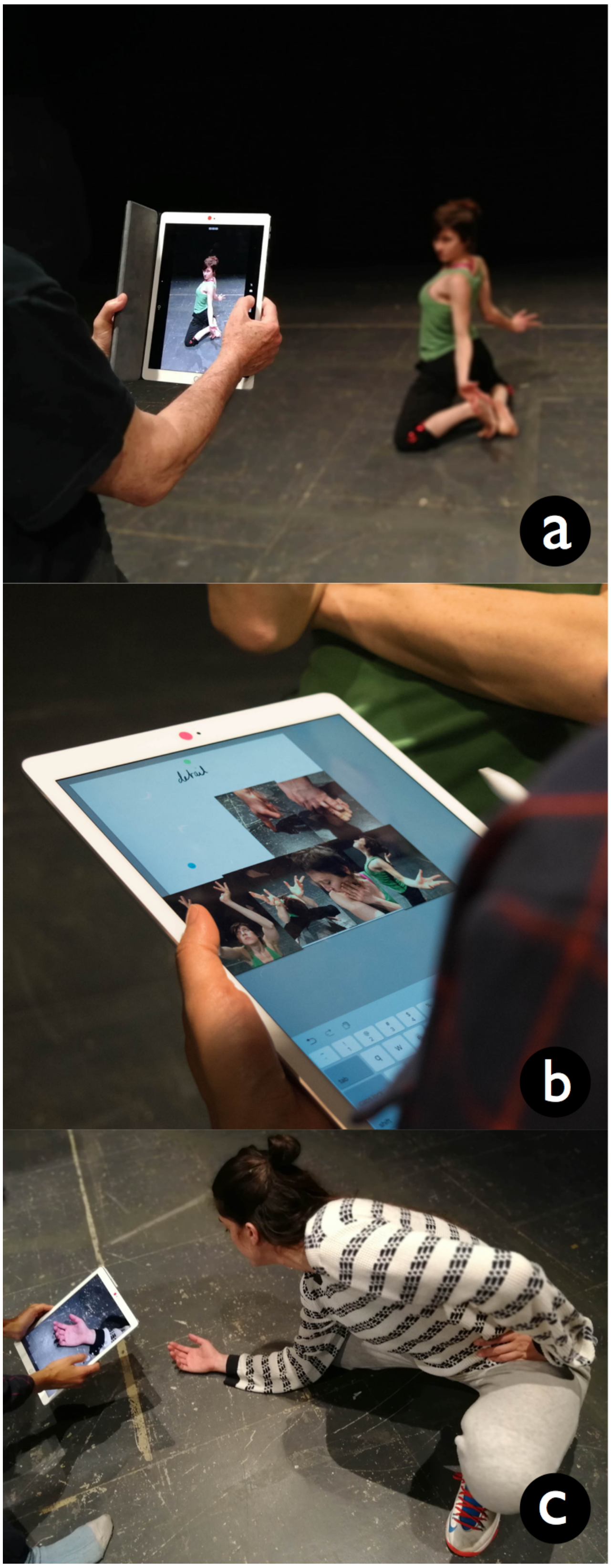

Figure 78: Residency: A dancer rehearses a dance sequence, filmed by C2 (a). C1 imports pictures into *Knotation* to document key choreographic moments (b). C1 takes a close-up video to revise a precise posture (c).

version of each of the other participants (including C2's) to create a global score on her own iPad (Fig. 78b).

Using Knotation sparked ideas among the choreographers

Having access to *Knotation* made C2 want to film close-up videos to identify little details about movement (Fig. 78c), which the dancers appreciated. For example, P1 said: *"Having all these little details about the fingers, we wouldn't have ever revised it if [C2] didn't have the idea of doing the close-ups..."*. She said that it made her think about *"how do I create my little schemas on the iPad"*.

In Session 2, C1 said that she established a writing policy that includes playing a video and at the same time, *"tracing with the pencil the trajectory of the significant body parts that move"*, inside a floorplan (Fig. 79). She compared it to her previous annotations: *"Before, on my notebook, I never traced the gestures. Here [I do], because I can control the video and play the floorplan..."*. She said she would be *"applying this recipe to each phrase"*.

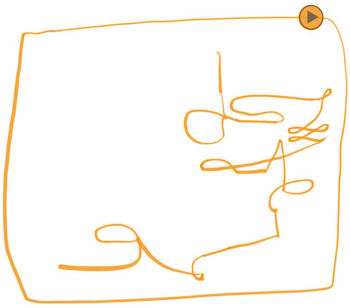

Figure 79: Residency: While playing a video of a dance sequence, C1 draws a trajectory representing the relevant body parts that move.

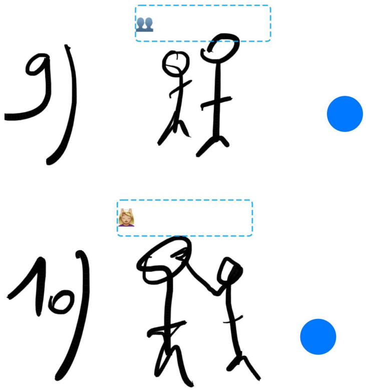

Figure 80: Residency: C1 uses emojis to tag sketches, but keeps the corresponding knots away from the textual tags.

TECHNOLOGICAL NEEDS AND APPROPRIATION CASES

Participants suggested a number of new features: assigning different colours to portals to recognise them[5], playing floorplans in loop, defining subsets of trajectories with a particular order on a floorplan, displaying images on timelines, and resizing *tag* knots so that emojis would show bigger. For P4, it was important to add more powerful edition possibilities for sketches (resizing, rotating, erasing specific parts). The choreographers were particularly interested in the global view of the piece. C1 requested more ways to manipulate and share the global structure (copying and pasting selected content within and across files, sharing her score by email without it being *"trapped in an application"*). C2 had a specific idea on how to visualise and manipulate his workspace. He wanted a *"pyramid with columns per dancer"* where each would have layers, for example *"a video layer, a rhythmic layer, a qualities layer"*: *"Like substrates: transparent layers on top of each other"*, that can be shown or hidden.

Participants also appropriated existing features for their own needs. For example, as images could not be played on a timeline, C1 filmed videos of less than one second. C1 discovered that multiple media could be added to the same knot, and she used this feature to replace simultaneous timelines, saving space on her canvas. C1 also figured out that it was possible to add emojis when writing text on *tag* knots. She found relevant emojis for the piece and put each tag close to the corresponding sketch, but away from its knot, to avoid cluttering the drawing (Fig. 80). Surprisingly, C1

5 *Knotation* supports the textual tagging of portals but participants wanted to also distinguish them by colour.

used the properties of spatial trajectories to express time-related movement qualities: She set the duration for a floorplan so that the system would calculate the speed of each trajectory, but she drew the trajectories shorter or longer so that they would take more or less time to be animated, simulating with this the temporal movement qualities she was looking for (Fig. 81). For her, these trajectories did not correspond to space or time, but to a combination of both so that the desired qualities could be reflected.

Figure 81: Residency: C1 uses the length of trajectories to convey temporal movement qualities rather than spatial ones.

DANCERS HAD CONTRASTING PERCEPTIONS OF KNOTATION'S VALUE

In contrast with the previous study, dancers reflected on *Knotation*'s value from a more active role beyond that of traditional performers, and expressed how they would use it as choreographers. Interestingly, two dancers had particularly contrasting visions about the possible uses, which highlights the importance of analysing this type of tools *in use* and reveals what are possible aspects of the design that prevent users from exploiting the tool's potential in each context.

P3 remarked *Knotation*'s potential for writing the piece from scratch, in a rich way that can still be transmitted to others: *"From the beginning I loved to have a tool where you can add videos, photos, different types of information that for us is very important because sometimes when we work on our notebook, it's very hard to write your choreography... 'Lower the head, bend right knee' implies an interpretation but being able to do it in* Knotation, *filming and having the material there, I think it's the bomb. I think it's very interesting as a work notebook to generate something, to start with that"*. He also referred to the value of *Knotation* for collecting multimedia references: *"I have notebooks with collages... And with* Knotation *I could do all that digitally in a quick and easy way, so that's why I think that if I had had it at the moment of facing a new creation..."*. He saw *Knotation* as a tool *"less rich"* for the end of the process, but still an interesting way to show the piece to external people such as journalists or other choreographers, *"as an a-posteriori diary of the work"*.

P4, instead, found it *"unnecessary for a draft"* and *"useful for the documentation of a final version"*, but perhaps for an assistant and not for himself as a choreographer. He said he prefers to *"make mistakes on paper"* and use the tool to pass from a draft to a neat copy: *"As a documentation tool I find it interesting, once you finished your creation process. You film videos, you put them, you make a neat copy..."*. For him, *Knotation*'s missing features, such as resizing and rotating sketches, restricted its potential for exploring ideas.

Three dancers (P1, P3, P4) mentioned the ludic aspect of *Knotation*. P3 said that *Knotation* was a *"playful tool"* because it allows animating trajectories. P1 described it as a playful way of gathering knowledge about the piece: *"Here we can include video, it's that the aspect that is playful, entering inside windows where you have the videos, photos, drawings, even though I'm for paper, I can't do that [on paper] (...) It's super cool to have everything together"*. P3 valued the possibility of hiding and triggering information in *Knotation* rather than just gathering it: *"Knotation has this amusing thing where you can put a dot that pops up a picture of the dancer, it makes it rich and playful. The fact of being able to have [knots] that open pictures, that play videos... That's very dynamic, that's very shareable! It's very cool because it's playable..."*. He added: *"This is digital and you can hide things and make them emerge when you want to see them, that's what is cool"*.

8.7 SUMMARY

I followed a professional dance company with two choreographers and four dancers during a 3-day residency. I introduced *Knotation* and observed how they used it.

None of the dancers identified problems of collaboration with other dancers, and similarly, the choreographers did not report problems with each other. Disagreements were seen as a natural part of collaboration, and participants appreciated their way of openly discussing to reach the same goal. The hierarchical division between choreographers and dancers was considerably less pronounced than in the previous study. Although participants perceived the existence of *"two sides"*, some dancers required, in fact, more distinct roles in terms of decision making. In earlier stages of the creative process dancers had had to transmit to each other the phrases they had created. One dancer reported that having a sense of ownership over the generated material favoured the horizontal communication between dancers, and consolidated their feeling of membership.

Each choreographer had their own style of using *Knotation*: While C2 delegated part of the score writing to the dancers, C1 created her own and wanted to incorporate the others' annotations into hers. *Knotation* was perceived by most dancers as a *"playful"* tool to gather knowledge about the piece, but also as a possible medium to transmit the work to external people, such as journalists or other choreographers. Some dancers had contrasting perceptions on what was the main potential of *Knotation*: For one dancer it was richer at the beginning of a creation, to collect inspiring sources and progressively annotate the piece. For another dancer it was more useful at the end, to document only the final decisions in a neat copy, or even to be used by an assistant to the choreographer.

The introduction of *Knotation* sparked discussions among the whole team about how to notate dance. Participants incorporated video and their scores in *Knotation* as additional mechanisms to transmit choreographic content. They did so in a horizontal way, where both dancers and choreographers were involved in the writing and the sharing of knowledge about the piece. In addition, using *Knotation* made one of the choreographers want to film close-up videos to identify subtle details in already familiar movement sequences. Dancers appreciated this initiative because it allowed them to revise aspects they were taking for granted after performing the piece several times. Participants appropriated available features, and suggested specific new ones or extensions to the existing.

8.8 DISCUSSION

The two studies described in this chapter involved the participation of twelve dance artists in total (two choreographers and ten dancers). One of the choreographers co-advises this thesis. Naturally, her familiarity with *Knotation* and the design rationale behind it are deeper than that of any other external user. However, I do not intend to present our findings as an evaluation of *Knotation*. Instead, these studies are concrete examples of studying the choreographic creative process when mediated by a digital tool in real-world collaborative settings. For logistic reasons, I was not able to observe participants outside of the dance studio, which restricted my opportunity to get insights on how they continue their creative process in other contexts. Still, I had 32+ hours of video from the first study and 24+ hours from the second, as well as notes, pictures, interviews with all the participants, and the logs of their interaction with *Knotation*.

Both field studies present two communities of practice — choreographers and dancers — who work collaboratively to create a choreographic piece. Each had access to the same digital tool with the same features, but showed fundamentally different uses and reactions to it according to their role. This highlights that it is not the tool itself, but the tool *in use*, what is relevant for studying collaboration, and what shapes the users' expectations and perceptions. In the first study, once other interactive technologies were integrated into the creative process, the dancers' level of engagement increased, affecting both the social dynamics and the use of *Knotation*. In the second study, the dancers were also choreographers and more involved from the beginning in the creation of choreographic material. For this reason, the hierarchical division was more horizontal and with richer, nuanced discussions. Yet, these two communities still had defined roles and lived sometimes *"in their own universe"* (C2), taking responsibility of separate aspects of the choreographic creation process: Dancers prioritised physicality and embodiment, while choreographers focused on revising the material, the global structure, and providing external feedback. After the introduction of *Knotation*, these two universes got together into a common ground when trying to create a digital score for the piece. The choreographers appreciated this opportunity but remarked the importance for dancers to balance the *"embodied"* and the *"intellectual"* ways of working (C2).

These results show how fundamental it is for tools such as *Knotation* to flexibly support collaboration in choreography. In particular, the studies revealed three types of collaboration that tools for choreographers should respect and let coexist, rather than try to replace: Collaboration between people (for example, when they negotiate choreographic or notation aspects); Collaboration between people and technology (for example, when they get inspired by the tool or when they use it to reflect on how to notate dance); and collaboration between people through technology (for example, when they use the tool to transmit choreographic material).

8.9 IMPLICATIONS FOR DESIGN

COLLABORATION AMONG PEOPLE

Support conflicting notation styles

Participants already had mechanism to discuss, negotiate, and transmit choreographic ideas without digital technology: They do so orally, with a common vocabulary that develops along the process (e. g., naming dance phrases, transitions, transformations, etc.), and by dancing. Participants also had their own style of notating dance, often times incompatible with other collaborators' methods. When participants notated collaboratively using technology they needed to agree on a policy. One possibility that I observed was to simply appoint a single person to notate the piece, negotiating (or not) how to structure the score and what type of information to record. Alternatively, other participants organically took turns to write and sketch, in a more exploratory way without much planning.

I argue that these strategies should not be replaced with a technology that forces users to adopt its own notation or choreographic approach. Instead, tools should recognise this diversity and allow users to manage conflicting styles of notation. Additional features could be provided, for example: having different ink colours so collaborators can recognise later who wrote what, as well as show or hide the annotations made by a particular person; and having explicit ways to associate two annotations to the same choreographic object, so collaborators could create explicit multiple representations of the same idea, each in their own style[6].

collaboration between people and technology

Leverage ludic aspects of interactive tools

Several participants perceived a ludic aspect in *Knotation*, related with the dynamism with which the user can show, hide, and trigger information depending on their communication goals and who is the interlocutor. Given that choreography is a highly dynamic activity, it makes sense that the way of representing it is also interactive. I believe that tool designers should not try to imitate a paper notebook, nor replace it, but rather exploit the interactive and ludic side of digital tools in order to engage users and spark new ideas.

Facilitate transitions from drafts to final versions

One participant felt frustrated by the lack of more advanced edition features in *Knotation*. Some users might not be at ease with using a digital tool for creating a draft of a document, and making *"digital mistakes"*. The question on whether providing more control to the user regarding sketch editing would change this perception remains open for future work. I also observed that several participants were concerned about the aesthetics of their scores, so I suggest that a smooth transition from a draft to a neat copy should be provided by design. For example, allowing the user to select a handwritten element and easily replace it with typed text[7].

collaboration between people through technology

Combine synchronous and asynchronous communication

The results suggest that having a global, synchronised repository of team members' documents would not be enough: Collaborators still need the others to explain them either the logic behind their annotations, or specific details not included in the documentation. This interaction could be held during studio time or outside. Tools for choreographic collaboration should be mobile so they can be brought to the studio, but should also pro-

6 Users can currently accomplish this in *Knotation* but without an explicit visual representation of a link.

7 This could be achieved using a technique such as Xia et al.'s (2017) *flexible representational axes*.

vide asynchronous communication channels to handle exchanges when participants are not collocated, as in Cherry et al. (2012). However, we found that some collaborators are not interested in having access to other people's personal version of the choreography, but still want to share multimedia resources and discuss how to notate the piece. Designers could provide a shared space where resources such as videos, images, and text are separated from personal notation, so collaborators can easily pick the material they care about. Naturally, privacy issues in the access to this information should be taken into account and be clear for the users. I believe that when collaboration is mediated through technology, both synchronous and asynchronous interaction can benefit collaborators. Though using technology in studio time consumes indeed a scarce resource, it also triggers interesting discussions and new ways of collaborating. The key, to my view, is not to enforce one way of working or the other, but to let users decide based on their social dynamics and transition seamlessly between different contexts of use.

Let collaborators choose their own roles

Even though the available features were the same for choreographers and dancers, the studies showed that choreographers tended to care more about the global structuring of the document or even wanted to centralise the sub-scores from other team members. This resonates with Cherry et al. (2012), where choreographers used comments to give corrections to dancers, but dancers did not comment so much on each others' performance. Though designers could work on sets of features targeted to choreographers and dancers separately, I argue for maintaining the same design while providing users with flexible ways to access shared resources and create their own workspace. Collaborators should be able to manage how they want to use the tool, both individually and as a group. In addition, as contemporary choreography tends to reinvent itself and redefine roles or create new, a design that considers only the traditional binary roles would constrain collaborators and hinder the evolution in the patterns of use.

8.10 SUMMARY AND CONTRIBUTIONS

Collaborative creative processes are shaped by the social relationships that emerge among content creators. The particularities of each creative field pose specific challenges for the design of relevant interactive tools. Choreography is especially complex, as the roles of choreographers and dancers become intertwined and refined over time. The ephemeral nature of dance, the variety of writing and representations, and the diversity of styles across choreographers and dance companies all contribute to the difficulty of creating appropriate tools.

Designing grounded CSTs for choreography requires the study of how professional choreographers collaborate with dancers and other choreographers, paying attention to the perspectives and expectations of each. This chapter presented two longitudinal field studies in which choreographers and dancers used *Knotation* as part of their creative process. *Knotation* was originally designed to let choreographers sketch their ideas and render them interactive, but was used here in collaborative settings involving multiple users and devices. The first study followed a choreography course with a choreographer and a group of students, over five months. The second study followed a professional dance company with two choreographers and four dancers, over a three-day residency.

The results show that choreographers' and dancers' annotation practices were affected by the social dynamics among them, in particular by the distribution of agency and responsibility, but also shed light on how introducing *Knotation* affected relationships among collaborators and the creative process itself.

I identified three types of collaboration that choreographic tools should support: Collaboration among people (negotiation); collaboration between people and technology (ideation, reflection, and transition to refined versions of the choreography); and collaboration among people through technology (synchronous and asynchronous transmission of choreographic material).

9 DISCUSSION

In this chapter I reflect on the challenges of designing interactive tools to support the creative practice of designers and contemporary choreographers. The first part of this thesis studies spatial constraints in a limited, controlled environment within graphic design. The second part implies jumping into a much more complex landscape involving multiple types of constraints, with multiple people collaborating in the exploration and documentation of multimodal ideas in contemporary choreography. Although their creative product is fundamentally different in nature, these professionals' creative process can be approached with a common strategy: The reification of structures through interactive substrates that articulate content and constraints.

DESIGNING TOOLS FOR THE CREATIVE PROCESS, NOT ONLY FOR THE CREATIVE PRODUCT

The nature of the creative product (digital, analogue, or hybrid) affects how dependent of digital technology is the creative process. Still, it does not determine the characteristics of the process in terms of representations of ideas (e. g., text, diagrams, sketches), supports (e. g., paper, video, dedicated software), or creative phases (including patterns of exploration and documentation). For this reason, designing tools that support expert creative practice requires to consider not only the nature of the creative product — which tends to highly vary from discipline to discipline — but also the nature of the creative process.

The design tasks targeted in this thesis heavily depend on digital tools to develop the final product of the creative process, as the product is typically organised around digital documents. As shown by Maudet (2017), although designers' methods are unique and evolve over time, the choice of digital design tools is often taken for granted and rarely questioned. Moreover, as argued by Candy (2007) in the context of digital art, some professionals cannot separate at all the tool from the medium. This might increase the creative agents' resistance to adopting new tools, unless the benefits outweigh the costs. Such tools could help professionals recognise and break from their habitual solutions (pushing them in breadth), directly build on their current practices (pushing them in depth), or both. There is a set of expectations that they bring to the encounter with each new tool about what it *should* provide. Meeting these expectations, or even defying them, is a risky challenge for tool designers. For example, unlike mainstream systems, *StickyLines* makes alignment and distribution first-class objects that have a visual representation on screen, and a behaviour that, though flexible, designers need to learn to use.

By contrast, the final product of the creative process in contemporary choreography is a dance performance, not a digital document. During the process, most choreographers do generate choreographic artefacts, some of which are analogue (e. g., sketches and notes on paper) and some digital (e. g., photographies, video of rehearsals, diagrams, etc.). Some choreographers also create very detailed scores of every part of the piece. However, these are all *representations* of the dance — not the dance itself. Although choreographers are increasingly using technology to capture different phases of their creative process, they do not *depend* on a digital tool to make a dance piece. This implies that their initial expectations from such a tool would not be defined in comparison with habitual digital tools of the same nature, unlike designers who usually have acquired habits associated to their preferred pieces of software. Instead, expectations are more likely to be based on how tools could support their well-oiled choreographic methods (which they develop with the dancers over time, adapting them from project to project), or on how tools could challenge their habitual ways of creating movement. Moreover, not every contemporary choreographer is interested in using an interactive system to support exploration and documentation of ideas.

I believe that this needs to be bear in mind when designing for an artistic discipline whose main medium is not a digital one. In this regard, Carlson et al. (2014) proposed to design systems for choreographers as collaborators instead of tools. They argued that to act as collaborators, systems should include some sort of creative agency to help choreographers generate original ideas. Even though this is an interesting position, I built *Knotation* as a tool rather than as a collaborator. I envisioned the role of *Knotation* as a lightweight, mobile tool that choreographers could use both outside and inside the studio to track the progress of their choreographic ideas and to be an object with which they could think. I purposely designed it to avoid directly intervening in (let alone replacing) the physical work that happens in the studio with the dancers.

Supporting exploration and documentation of creative ideas

The nature of the creative product alone does not determine the patterns of exploration and documentation of ideas during the creative process. At first sight, it could be tempting to say that designers can explore their ideas using exclusively digital CSTs while choreographers must at some point explore them through movement (performed by themselves or by the dancers). However, designers often combine dedicated CSTs with other more general representations and supports such as paper, sticky notes, slide presentations, videos, bookmarks, etc. (Inie and Dalsgaard, 2017a,b). In contemporary choreography, a large part of idea exploration indeed happens outside of CSTs (in movement generation or improvisation sessions, in rehearsals, or even in performance). Still, as shown in this thesis, choreographers also engage in early exploration of ideas through sketches, text, and diagrams, on paper, word processing and graphical editing tools.

In both design and contemporary choreography, the creative product could be developed without documenting the creative process. However, both types of practitioners document it to some extent, sometimes even including ideas that do not belong to the current project but that they want to save nonetheless.

As demonstrated in this thesis, the limits between exploration and documentation are sometimes blurred. For this reason, I argue that tools to support expert creative practice should consider both exploration and documentation in flexible ways, and should not expect users to *only* use their CST. As shown in Part I, *StickyLines* supports the exploration of alignment and distribution constraints. At the same time, it documents the final decisions by leaving traces of interaction, i. e. the persisted stickylines that the user saves with the document. As demonstrated in Part II, *Knotation* provides both exploration and documentation of spatial and temporal constraints. Choreographers can use it to actively explore ideas (as the participants who adopted *record-then-dance* strategy), which creates the documentation on the go. Alternatively, they can explore ideas by moving (as in the *dance-then-record* strategy) and then use *Knotation* to document the final decisions (including content, constraints, or both). They can also go back and forth between the tool and the movement. Regardless of these patterns, choreographers can complement *Knotation*'s documents with other choreographic artefacts (such as diagrams or sketches on paper notebooks), or even incorporate them to the tool by taking pictures of the relevant pages.

REIFYING STRUCTURES TO DESIGN CONSTRAINTS AND CONTENT

A common thread in this thesis is the reification of structures that users develop and rely on during their creative process. Reifying structures is a way to build *"scaffoldings for thought"*, which Kirsh (2010) considered a fundamental part of cognition. In particular, he discussed the cognitive benefits of using *representations*, highlighting their role as providers of structure that can be used as a *"shareable object of thought"*, as *"persistent referents"*, and as coordinators of thought. Moreover, Kirsh argued that *"physically reifying a shape through annotation adds something more than just providing a shared reference; it provides a persistent element that can be measured and reliably identified and re-identified"*, which is exactly the case in both *StickyLines* and *Knotation*.

StickyLines helps designers structure their layouts, acting directly on the elements that actually form part of the final creative product (graphical objects in a digital document). *Knotation*, instead, helps choreographers structure their dance pieces, acting on *representations* of the elements that constitute the final product (including dancers, stage, movement, transitions, etc.). In the specific case of choreography, Kirsh (2009) stated that *"imaginary structures"* can be used as scaffolds for dancers, especially when they do not have a partner to interact with — or, in *Knotation*, when the choreographer is working alone before interacting with the dancers in the studio. Along the same lines, deLahunta (2015) posed Forsythe's Improvisation Technologies (Section 7.1) and Brown's Locus (Section 3.5.2) as examples of *"the generative potential of structuring a mental space through thinking systems involving points, lines and planes"*. Moreover, Forsythe referred to *Improvisation Technologies* as a way of *"taking mental note"* while moving: *"It was easy to represent things this way — thinking in circles and lines and planes and points"* (deLahunta, 2015).

SUBSTRATES: SETTING THE CONDITIONS FOR THINGS TO HAPPEN

This thesis uses substrates as a means of making users' structures interactive and under their control. Substrates operationalise a set of reified constraints and their associated content, articulating the relationships between constraints and containing the user's data (e. g., the graphical objects in *StickyLines* and the choreographic objects in *Knotation*).

When content lives inside a substrate, changes in constraints propagate to content. Because the substrate exposes the rules that govern content, it can also react to changes in the content in such a way that helps the user detect incompatible decisions within current rules, i. e. broken constraints. The user can then decide to either adapt the content or manipulate the constraint: e. g., bend it, break it, or remove it. For example, in *StickyLines*, if the user does not like how an icon looks on a stickyline, they can manually position it where they prefer. The system visually exposes this tweak to indicate that the object is still logically attached to the stickyline. This serves as a way to bend the alignment constraint without breaking it.

Having specialised substrates helps the user divide a complex problem into layers. For example, in *Knotation*, the user can compose space and time separately when they want to focus on each aspect individually, or superimpose them when they want to examine their combination (for example, by drawing a line that works as both as a spatial trajectory in a floorplan and as a temporal timeline).

Substrates support the co-adaptive phenomenon between users and technology, which is a perspective more user-centred than the design principles associated with instrumental interaction: Substrates help the user to *adapt to* the system, as they facilitate learning through exposing the current constraints. For example, in *StickyLines*, the user knows when distribution is active, because the distribution type is *on*, the reference points are highlighted in red, and adding an object to the stickyline automatically recomputes the layout. In *Knotation*, every time the user changes the speed or duration of a floorplan, it gets automatically played to reflect the change immediately. Substrates also help the user to *adapt* the system. For example, in *StickyLines*, tweaking reference points or bounding boxes results in the system visually showing the change and persisting it.

Klien (2007) wrote an essay about the shift of contemporary choreography from structuring information in time and space, towards a *"recognition of interconnectedness: the creative act of setting the conditions for things to happen, the choreographer as the navigator, negotiator and architect of a fluid environment"* of which they are a part. This applies to design as well, as designers also engage in creatively *setting the conditions for things to happen*, as evidenced by the *graphical substrates* defined by Maudet (2017) and on a smaller scale, by the studies with *StickyLines*.

This thesis shows how interactive substrates directly address *interconnectedness*. They allow users to express, manipulate, and reflect on constraints in order to *set the conditions for things to happen* — and even figure out what those conditions are. The user can express constraints, articulate them into a substrate, and interactively manipulate both content and constraints in it. Constraints can be added, further specified, removed, changed, replaced, tweaked, or broken, and the user can observe the effect on content immediately. By interacting with the substrate, the user can also visualise and assess existing constraints or discover new ones. Extending the decoupling of constraints from content (for example by enabling the linking of objects as envisioned in Sections 5.11 and 7.10) could let the user define a minimal set of constraints, which could easily be saved, loaded, and replaced for a different set to quickly explore their effect on content.

In summary, *StickyLines* and *Knotation* target different audiences, different types of creative products, and different problem scales. In spite of these differences, they were both designed following the same set of design principles, and they lead to similar user behaviour: Once their ideas are reified and made interactive through substrates, creative professionals engage with the tools and want to push the interaction forward. They express content and constraints, designing and tweaking them to better match, challenge, or discover their own creative principles.

LIMITATIONS OF SUBSTRATES

As shown in the conducted studies and in the literature review, creative professionals often make decisions upon content based on the possibilities outlined by a set of self-imposed constraints. However, they sometimes rely on their intuition, without explaining to themselves or to others *why* they make a certain creative decision — because they cannot, or simply do not want to. For example, in the interview study from Chapter 6, one of the choreographers referred to the mapping between a conceptual idea and a concrete movement as *"evidence"*: *"It's obvious, it has to be that, and nothing else"* (P6). In some cases, the practitioner succeeds at articulating and transmitting a constraint through a certain representation (e. g., words, sounds, movements, numbers, diagrams, sketches) but the representation does not capture all the richness and nuance behind the idea. For example, asking a dancer to generate a movement that expresses "the colour blue" is a constraint that can be captured in *Knotation*, but programming a system's response that *enforces* this constraint implies interpreting it.

For a substrate to be interactive, it is necessary to formalise and articulate its components and behaviour to some extent. Some constraints are, by nature, too abstract and subtle to be represented in a way that computers can unambiguously interpret. This is often the case in contemporary choreography, where choreographers use this ambiguity to spark creative responses. For example, as shown in the *Choreographic Object-Operation* framework (Section 6.4), contemporary choreographers purposely leave elements unspecified: Rather than concrete instructions, they use constraints as triggers for dancers to (re)interpret and creatively problem-solve.

In this context, where the constraints in play are not sufficiently described at *any* point of the process in order to map them to specific system's responses, an interactive substrate does not provide any particular benefits to the creative agents. Moreover, I argue that the situation would require human creativity and human interaction. The role of the technology, if any, would necessarily have to shift from a *tool* to a *collaborator* with its own agency, which is, for the moment, outside of the theoretical limits of substrates.

Still, as discussed in Section 7.9.4, a CST based on substrates does not prevent users from employing a *content-based* strategy, i. e. documenting exclusively content without traces of constraints. I believe that storing such content in an environment that allows the *post-facto* addition of constraints is more likely to open new paths than to restrict them.

10 CONCLUSION

This dissertation explores how to design interactive tools that support expert creative practice. I focus on graphic designers and on contemporary choreographers. Both types of practitioners develop their creative ideas according to personal underlying principles, which they sometimes generate, discover, or challenge during the creative process. In order to do so, they define the *content* in their creations, and the *constraints* that shape this content.

Graphic designers must often establish spatial constraints between the graphical objects in a layout, and in particular, alignment and distribution constraints. They frequently have to handle their creative principles and constraints manually, as existing digital tools do not support their practices in flexible ways. Contemporary choreographers work with spatial constraints but also with temporal and more complex constraints, such as movement qualities, metaphors, or intentions. In addition, choreographers need to consider the interaction between constraints and dancers, who can interpret and redefine them. Choreographers seldom have access to digital tools specifically created for choreography. Designing such tools is challenging because contemporary choreographers develop personal methods and styles that sometimes challenge the field's rules and their own vision, and some even adopt drastically different approaches with each new piece.

I sought to support these creative professionals in defining and manipulating constraints from the beginning of their creative process throughout the transition to later stages. To achieve this, I studied real users' practices and I built appropriable tools grounded on their higher-level commonalities. *StickyLines* and *Knotation* both offer concrete representations of constraints without enforcing a predefined set. They support users in exploring content, constraints and their relationships, allowing them to discover creative principles and interesting patterns. For example, *StickyLines* detects potential relationships and suggests them to the user as they play with objects' positions, and provides reshaping of stickylines for the user to try until finding a pleasant spatial configuration. *Knotation* lets the user write and sketch ideas from scratch and combine them with multimedia sources of inspiration. The user can start from high-level ideas that get progressively defined, or from examples (such as video clips of dance sequences, or formal notation).

SUMMARY OF CONTRIBUTIONS

In the first part of this thesis I explored the definition and manipulation of alignment and distribution constraints in the design of graphical documents. I first studied the practices of 12 designers and regular users of graphical editing tools. I identified three issues that they face when interacting with current software: lack of persistence, lack of control, and lack of generality. These results suggest that participants perceive alignment and distribution as relationships among objects, but current tools implement them as actions to be performed independently of existing relationships.

Based on these findings, I built *StickyLines* to provide persistent, fine-grained control over alignment and distribution, as well as more general capabilities. *StickyLines* reifies the concepts of aligning and distributing graphical elements into first-class objects that users can create, customise, control, and reuse. Through a controlled experiment and a structured observation, I showed that *StickyLines* not only can support designers' practices but also benefits a more general audience: It is faster and requires fewer user actions than command-based systems to create complex layouts, and better matches how users perceive relationships among visual objects. *StickyLines* accommodates users' diverse design strategies: starting with constraints and then manipulating content, doing the opposite, or a mix. Via tweaks and bounding box manipulations, *StickyLines* breaks the binary nature of alignment and distribution, allowing users to embed their personal style. The *StickyLines* approach illustrates how the design principles in instrumental interaction and substrates can be combined to support spatial constraints, by turning them into true objects of interest.

In the second part of this thesis, I sought to support the definition and manipulation of spatial and temporal constraints in the exploration and documentation of ideas in contemporary choreography. I studied the current practices of contemporary choreographers to have a better understanding of how do they capture and manage choreographic ideas in their creative process. I was interested in what kind of artefacts they generate and how they handle the evolution of their ideas within the great diversity of approaches to dance and choreographic practices.

I synthesised the higher-level patterns in participants' idiosyncratic practices into the *Choreographic Object-Operation* theoretical framework: *Choreographic objects* are expressed with a certain degree of *specificity* through different *representations*. They evolve through several *creative phases* as the choreographer applies *operations* to them, shifting among *focal points*.

Then I derived a set of implications for the design of digital tools for choreographers in the context of exploring and documenting choreographic ideas: Tools should make the knowledge about the piece available, enable shifting across levels of specificity and focal points, and support both situated action and distributed cognition. Combining these implications with the existing literature, I argue that these digital tools should support free sketching, integrated images and video, and multiple representations and views of choreographic objects. Choreographers should be able to draw the overall structure of a piece, and transition easily between abstraction and detail.

I then used the operations in the framework to spark choreographic activities in an observational study with choreographers and dancers. Results suggest that choreographers want to express choreographic concepts in terms of both space and time, and to represent movement in terms of constraints, through combinations of drawings, text and numbers.

Based on these results and what we learnt from *StickyLines*, I built *Knotation*, whose design was refined through the input from choreographers and dancers. *Knotation* is a pen-based mobile tool that lets choreographers sketch choreographic ideas and make them interactive. Users can sketch their own personal representations of the dance, and add various forms of interaction to further explore their ideas, including creative constraints. *Knotation* allows choreographers modify the meaning of particular choreographic objects, delay decisions, and freely explore different combinations.

I presented a technology probe study with choreographers using a first version of *Knotation*, and a structured observation of choreographers using a second version. *Knotation* successfully supported opposite choreographic approaches (*dance-then-record* and *record-then-dance*), and allowed users a wide range of expression, at varying levels of formality. I showed how the design principles behind *Knotation* support choreographers in composing time and space. The substrates approach illustrated in *Knotation* supports a range of user strategies, from completely based on constraints, to completely based on content, including strategies that start with constraints and develop content around them, strategies that adopt the opposite procedure, and mixed strategies.

As the presented studies did not delve deep into the collaborative aspect of contemporary choreography, I ran two longitudinal field studies to capture collaborative practices and needs of choreographers and dancers. In these additional studies, I examined the relationships among choreographers and between choreographers and dancers in the context of using *Knotation*. The results show that choreographers' and dancers' annotation practices are affected by the social dynamics among them, in particular by the distribution of agency and responsibility, but also shed light on how introducing *Knotation* affect relationships among collaborators and the creative process itself. I identified three types of collaboration that tools should support in this context: Collaboration among people (negotiation); collaboration between people and technology (ideation, reflection, and transition to refined versions of the choreography); and collaboration among people through technology (synchronous and asynchronous transmission of choreographic material).

MULTIDISCIPLINARITY AND THESIS POSITION

This thesis in Computer Science is framed within the theory and methodologies of HCI, while borrowing knowledge and inspiration from design and dance literature. Its contributions are relevant for researchers in these three disciplines, as well as for designers of creativity support tools. Yet, the development of this thesis implied the collaboration of designers and dance artists, who participated voluntarily in the conducted studies giving us their time and invaluable insight. Their benefits consisted of reflecting upon their own practice, and exploring novel tools.

Through *StickyLines*, I examined alignment and distribution in depth. Naturally, *StickyLines* does not include all the features of a commercial graphics editor, as I was not interested in building a tool to replace mainstream systems, but in providing a new way to think about spatial constraints. However, the developed techniques can easily be picked up by both the industry and the open source community to incorporate them into their software[1]. Hopefully, the inclusion of instruments such as stickylines will make tool designers rethink how they approach other spatial relationships in a layout.

In the context of a collaboration between HCI and dance, the tension between the live dance performance and its documentation needs to be considered. deLahunta and Shaw (2006) recognised this tension but also a shift due to two factors. One factor was the change in what constitutes a useful resource for researchers working in multidisciplinary areas, as is my case. The authors noted that the creative process in artistic fields, rather than the creative product itself, started gaining attention as a source of knowledge for other fields. For example, Loke and Robertson (2007; 2010; 2013; 2015) studied dance artists' meth-

1 For example, a designer who found our publication, Ciolfi Felice et al. (2016), started implementing the techniques in his own design tool. Source: Post in the Mastodon social network, `https://vis.social/@monfera`, September 3, 2018.

ods to explore and document movement, and applied their observations to interaction design; and Fdili Alaoui et al. (2012) used movement qualities as interaction modality, showing that they enhance users' expressivity. The other factor was the artists wanting to share and reflect on their own creative process. deLahunta and Shaw speculated that this could be a response to researchers' increasing interest, or a longing for a *"self-demystification"* of their practice with the goal of sparking innovation. This trend is reflected in plenty of books and multimedia projects described in previous chapters (Sections 3.4 and 7.1), and by the fact that interviewed participants in this thesis have been eager to talk about their methods, goals, and perspectives, often way over past the planned duration of the interviews.

Transforming *Knotation* into a finished product that is available for continuous use by professionals is out of the scope of this thesis. However, its development could be continued and even challenged by future theses and research projects, leading to put this technical contribution in the hands of the dance community.

The role of technologists

As discussed earlier, technology brings opportunities and constraints to creative processes. One important source of constraints is the role of technologists in this context. Ventura and Bisig (2016) assumed that algorithms for choreography can be based on neutral and abstract principles that do not embed personal styles. I do not agree with this assertion, as the very act of creating an algorithm implies at least one human programmer. The people involved, intentionally or not, bring with them a set of values and assumptions about what is dance, choreography, movement, how is the human body, what can a dancer do, how does choreography relate to music and other arts, etc. In the design of *Knotation* I tried to work with the fewest number of assumptions, and to make the unavoidable as explicit as possible. For example, *Knotation* does not include lists of body parts, or visualisations of the body. The aesthetics are mostly based on what the user draws and how they interpret the strokes they produce: They could draw animals, geometric figures, non-anthropomorphic robots, etc. However, for the system to actually be interactive, I did have to make a selection of, for example, the movement attributes that *Knotation* would support. I chose speed, duration, quality, and energy, but another designer could have thought of a different set (including, for example, acceleration, rhythm, jerk).

10.1 LIMITATIONS

The presented contributions have a number of limitations. I discuss how to push further the design of *StickyLines* and *Knotation* in Sections 5.11 and 7.10, and the theoretical limitations of substrates in Chapter 9. Below I list the most relevant technical limitations faced in this thesis.

Separation of structure and data: In order to fully exploit the potential of substrates, a true separation of structure and data should be provided. This is an open technical challenge and especially difficult in choreography, as choreographers transition seamlessly between content and constraints and even keep fuzzy divisions between these concepts.

Operating systems and mobile devices: For the particular case of *Knotation*, the operating system and the fact that it runs on mobile devices are two additional sources of technical limitations.

Apple's iOS imposes a number of restrictions, for example, sandboxing (which limits the resources that an application has access to, e. g., files, network, hardware, etc.); background running (specific permissions must be obtained to run long tasks in the background without the application getting suspended); and synthesis of user events (e. g., faking touch to test the user interface is possible but cumbersome).

Mobile devices come with performance limitations that restrict interaction. For example, the AVFoundation framework only allows to play a certain number of videos at the same time. When testing *Knotation* in the lab, this number was often around 15. In the user studies, however, the limit was not reached, as the screen size is another limiting factor for users to watch many videos simultaneously.

10.2 PERSPECTIVES FOR FUTURE RESEARCH

The work conducted in this thesis opens the path for exploring other angles of the same problem from new empirical, theoretical, and design perspectives. Hopefully, it also invites researchers and tool makers to delve into the support of other creative disciplines putting constraints at the core of the design process.

Empirical perspectives

The nine studies conducted in this thesis contribute with evidence about how designers deal with alignment and distribution constraints in their work, and how contemporary choreographers manage a variety of ideas and constraints, both with their current tools and with the ones proposed in this research. A clear path for future work implies studying the use of *StickyLines* in long-term field studies where designers can collaborate with others and grow a layout over time. *Knotation* could be used in additional long-term field studies following more complex dance projects that span over months or years and involve a larger number of stakeholders.

Theoretical perspectives

The descriptive power of the *Choreographic Object-Operation* theoretical framework could be tested with more choreographers and even analysed in the framing of other performative arts.

New types of substrates could be explored by researchers and tool makers with the participation of graphic designers and dance artists. Playing with such substrates should not require users to program, although indeed more powerful opportunities could be offered to those who can code.

An exciting direction for future work emerges from combining substrates and linguistics. In the case of choreographic notation, relevant questions are: How could we support users' *personal sub-languages* (Section 6.7) and how would *notational substrates* would look like?

Design perspectives

Exploring other representations of constraints: Reifying alignment and distribution relationships into stickylines is not the only way to approach their handling. For example, the use of *"spacers"* (graphical objects that users create to manually handle space between elements) could be worthy of exploration, as well as the use of graphical properties of existing objects as generative constraints (such as colour, length, shape).

Similarly, timelines and floorplans are useful tools to organise and make sense of spatial and temporal constraints, but they are not the only possible representations for these types of constraints in choreography. Departing from *Knotation*, we can envision other interactive objects to design, for example, the temporal progression of dancers' levels based on interactive 2D curves. This new representation would emphasise a particular aspect of a spatio-temporal constraint — the height of the body with respect to the floor as it moves over time. In addition, I explored only linear temporal constraints in *Knotation*, but future research could address explicit representations of repetition and logical rules that trigger temporal events (*if-this-then-that*).

Supporting other constraints: Alignment and distribution relationships are not the only spatial constraints with which designers work. Similarly, the temporal and spatial constraints that can be expressed in *Knotation* cannot possibly cover the huge variety of creative constraints used by choreographers.

Supporting other types of constraints without cluttering the screen or increasing users' cognitive load remains a challenge. However, strategies to let users graphically define complex constraints (e. g., in the spirit of *Linkify*, by Maudet et al., 2017) could be integrated to both *StickyLines* and *Knotation* (or to new systems) to increase user control. In addition, random behaviour under user-defined constraints could be used to operationalise more complex users' rules. For example, a tool such as *Knotation* could generate numbers, choose elements from a list created by the user, permute the order of elements on timelines or floorplans, or even propose strokes and complex patterns. In all the cases, it should be made clear for the user that the system is randomly proposing solutions that meet the constraints, rather than being creative.

Including other tasks and contexts: *StickyLines* targets static layouts that do not respond to user interaction nor change with, for example, the time of the day. Interesting possibilities open up if considering dynamic layouts where designers need to keep objects aligned or distributed as they move. For example, dynamic, shape-changing stickylines could be implemented and tested. This would also deepen this thesis' empirical contributions, by studying how users perceive and manage groups of related objects over time.

Overarching perspectives

Designing for other creative disciplines: As I argue in Chapter 9, designing for the creative process and not only for the creative product enables us to approach the design of interactive tools from a higher-level of abstraction. It is intriguing to study, then, how the design principles used in this thesis may be employed to support other creative disciplines such as filmmaking, theatre, or interaction design: To what extent do the principles hold? Where do they break? Can they further challenge the concept of substrates?

Constraints as true objects of interest: Future work in supporting expert creative practice should consider the role of constraints as ways to structure content *and* as concrete objects of interest that users not only face when designing, but also want to *design*.

A

APPENDICES

A.1 USE CASE WITH A CHOREOGRAPHER IN A WORKSHOP

A choreographer who participated in the structured observation study in Chapter 7 asked us to lend her *Knotation* for a 3-day workshop that she conducted. I was not present in the workshop, but *Knotation* logs the interaction and captures screenshots periodically. I also interviewed the choreographer at the end of the week for one hour. The workshop was part of her transdisciplinary project combining *"gesture and text"* into a *"scenic dramaturgy"* (the choreographer). Ten actors participated in the event, plus a developer with whom she has been closely collaborating for three years. Around half of the actors were also authors or had their own companies.

The goal of the workshop was to present a set of available technologies and brainstorm script ideas for building interactive *"theadance"* — the choreographer's term for a type of art that mixes theatre and dance. The technologies involved the use of Kinects, speech recognition, vibration sensors, and a hacked stethoscope. A Kinect application that she built with the developer is capable of detecting actors' gestures to control the projection of images and video. The vibration sensors capture their steps to transform the music and compose new sound loops. The speech recognition system allows actors to *"talk with the machine"* via a chatbot. The chatbot *"learns"* as the users talk to it, replying with comments it has received from other users before. It can also generate new text based on *"poems that we [the choreographer and the developer] fed it with"*, and it is programmed to react to certain keywords, names, and to insist on specific questions. The electronic stethoscope had been hacked to transmit the sound in real time to a system that would map it to images. This was the first time that the workshop participants came in contact with, in the words of the choreographer, *"the creepy world of technology"*. The choreographer perceived them uneasy at the beginning, but getting more comfortable later, as they discovered the creative possibilities offered by the devices and algorithms.

The workshop was inspired by a previous project of the choreographer, which consists of 26 scenes. Each scene constitutes a different *"universe"* with a *"specific logic"* that governs the interaction between characters and technology, including a random component that prevents the piece from happening in the same way twice. She explained that in this type of piece *"there's a set of things that are pre-written, and you have to leave another set of things completely open to [provide] a capacity of improvisation that gives place to surprise and risk taking... The machine proposes things that you haven't foresaw, you need to adapt yourself, be able to follow them, or be able to say* 'no, I'll try to impose my choice'. *There's a dialogue between all the scenic elements, there's nothing decorative or isolated"*.

The first day, the choreographer described her vision regarding the use of technologies on stage. For her, it is fundamental to *"integrate the logics of the dramaturgy from the beginning"*, instead of first creating the choreography and then incorporating the imagery and the sound. She then introduced *Knotation* to participants and proposed them to use it to annotate script ideas, including characters, interactions with the technologies, use of space, etc. She divided the participants in two groups. One group worked with the developer, and the other with the choreographer. She picked the group that was less comfortable with technology, and noted that the younger participants *"got quickly into thinking in logic ways, for example,* 'if this then that', *the logic of programming"*. Her group had the iPad, while the other group used a paper notebook.

As a first activity, the actors read the text that they had each composed as a requirement for the workshop, about *"what is the human"*. While they read, the choreographer created portals in *Knotation* and sketched their body postures inside, to analyse them together later. She also wrote in *Knotation "the program of what we did in the morning"*.

Then the choreographer presented the technologies they could play with. She wanted participants *"to chose quickly the technologies"*, but they were not able to do so. Participants told her that they *"did not understand the logic"* and *"couldn't produce ideas"* in this logic unknown to them. The choreographer told me that *"because they [the actors] were not dancers"*, they felt less inclined to perform movements, and preferred speech as the interaction mode with the technologies. They were not able to use the vibration sensors for the sound because the flat wooden floor did not vibrate. The stethoscope was finally not used to map sensed sounds to images, but simply to auscultate the audience when they arrived, playing the sounds on speakers.

The choreographer also created a set of diagrams showing the stage and three screens. She put one *tag* knot per screen to name them, with the idea of adding images to the knots eventually, when she had the time. She said that the number and location of the screens was a constraint that had implications in their use of space. It made them reflect of what it means to use the three screens, where should they place the audience, what was going to be the audience's relationships with the interpreters in terms of space and interaction, etc.

The second day, the choreographer sketched some more but did not have time to take notes. She continued capturing script ideas, through text and portals. While discussing with the group, she wrote what they would have to program to accomplish their ideas. The choreographer asked a participant from the other group to write their ideas using *Knotation*. The participant created a storyboard with notes illustrating their ideas and explained it to the choreographer, but only used portals and some video knots.

Collaborating with a developer

Regarding the collaboration with the developer, the choreographer mentioned becoming aware of their *"shared language"* when the workshop participants pointed this out while hearing them talk. She said that some ideas came from the developer, affecting the artistic vision, and some came from her, the artist, affecting the way in which the developer approaches the programming. For her, the key is to have a collaboration dynamics in which she can ask *"Is this possible? How could we imagine this?"* rather than demand from the developer: *"Build this for me"*. She felt that sometimes there was a *"worlds separation between the functional part and the artistic part"*, and she advocated for working on both at the same time because *"they cannot be separated"*.

Using Knotation

The choreographer remarked: *"I love portals"*, but said that after considerable *"branching"* she found it hard sometimes *"to know where [she] was"*. She suggested to incorporate a feature to *"visualise a global scheme"* at the bottom of the interface, *"like a map"* with *"direct access to the pages"* from the miniatures. The choreographer had trouble understanding why three portals created by another participant lead to the same content, until she figured out that they were clones. An improvement would be to mark clones of an original portal for easy identification. She appreciated *"the different types of data: images, videos, notes"* that she could *"keep all together"*, in a *"much better and more interesting"* way than with a paper notebook. She wanted to be able to import PDF files (instead of pictures), and we discussed possibilities of annotating them with notes and knots.

The choreographer wanted to continue using *Knotation* to complete the documentation with floorplans and timelines. She stated not having used the tool *"as it was designed to be used"* due to lack of time, but rather employed it to *"document the exploration"* while interacting with the actors. The choreographer added that she would like to use *Knotation* again for her next choreographic creation, in a one-week residency where she can manage her time and *"enter on a writing phase"*, and in general, to *"design the technology"* in her future pieces.

A.2 ARTEFACTS CREATED BY PARTICIPANTS IN THE FIELD STUDY WITH A DANCE COMPANY

The following are interesting examples of choreographic artefacts that participants created with *Knotation* in the field study with a dance company (Section 8.5).

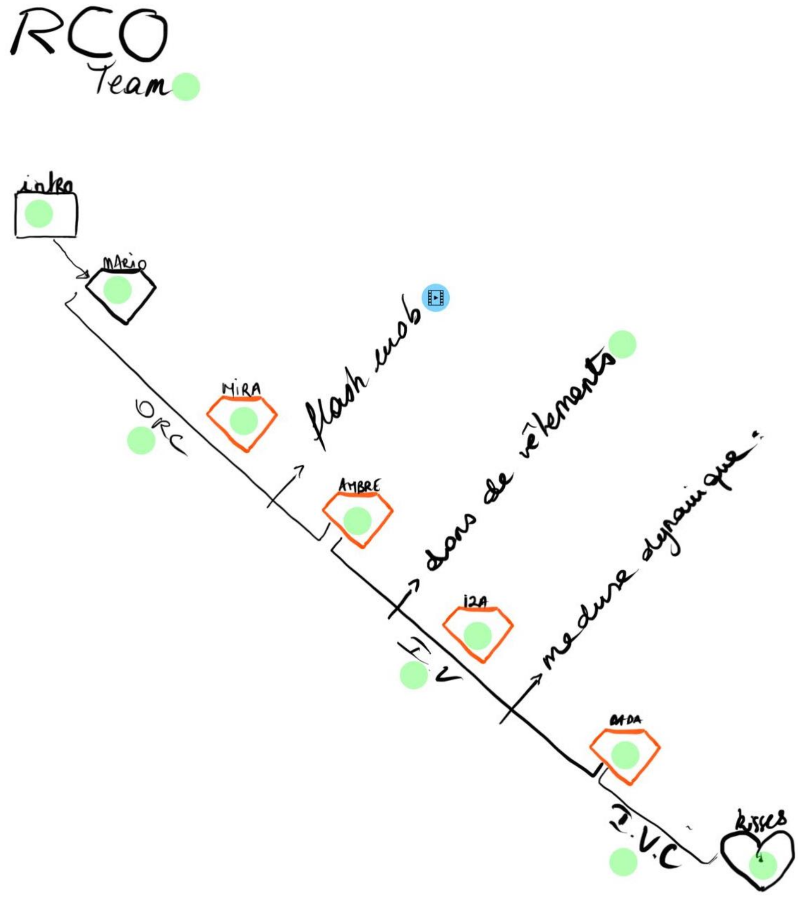

Figure 82: Residency: The main page in *Knotation* shows the general structure of the piece, with a portal for each part (P1 and P4).

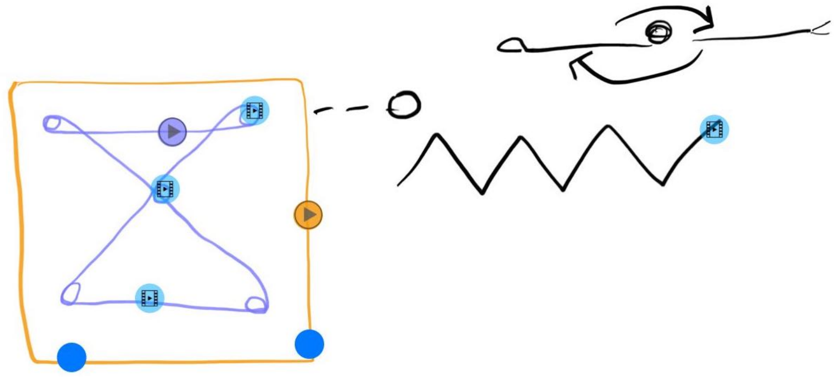

Figure 83: Residency: C1 represented a key dance sequence with a floorplan showing the dancers' spatial trajectory. The trajectory is also a timeline that plays the corresponding videos. On the right, C1 sketched the dancer seen from above (the circle is the head, and the arrows indicate orientation changes). Below, she included a video to exemplify the movements.

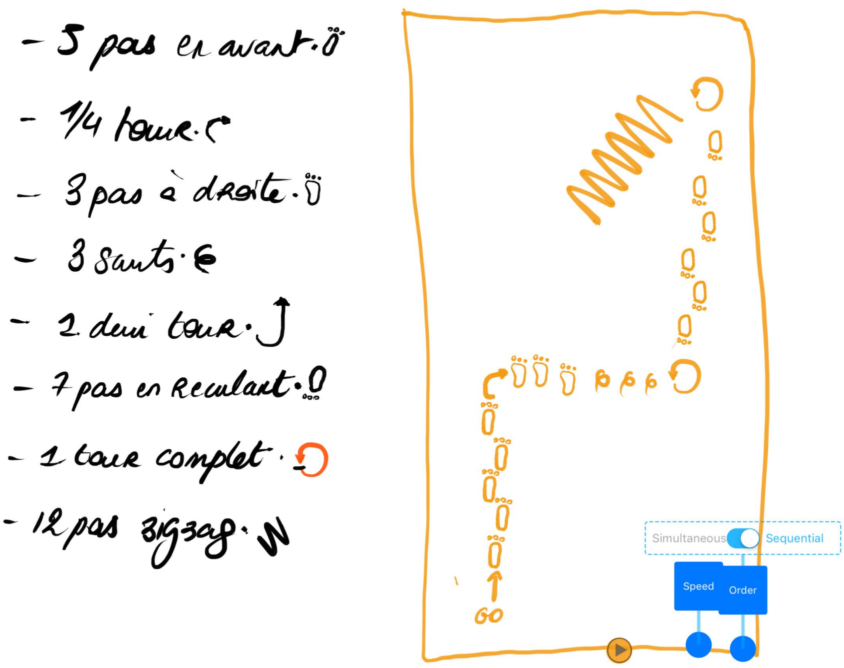

Figure 84: Residency: P1 and P4 created a floorplan for their part, including not only spatial trajectories but also symbols representing specific actions.

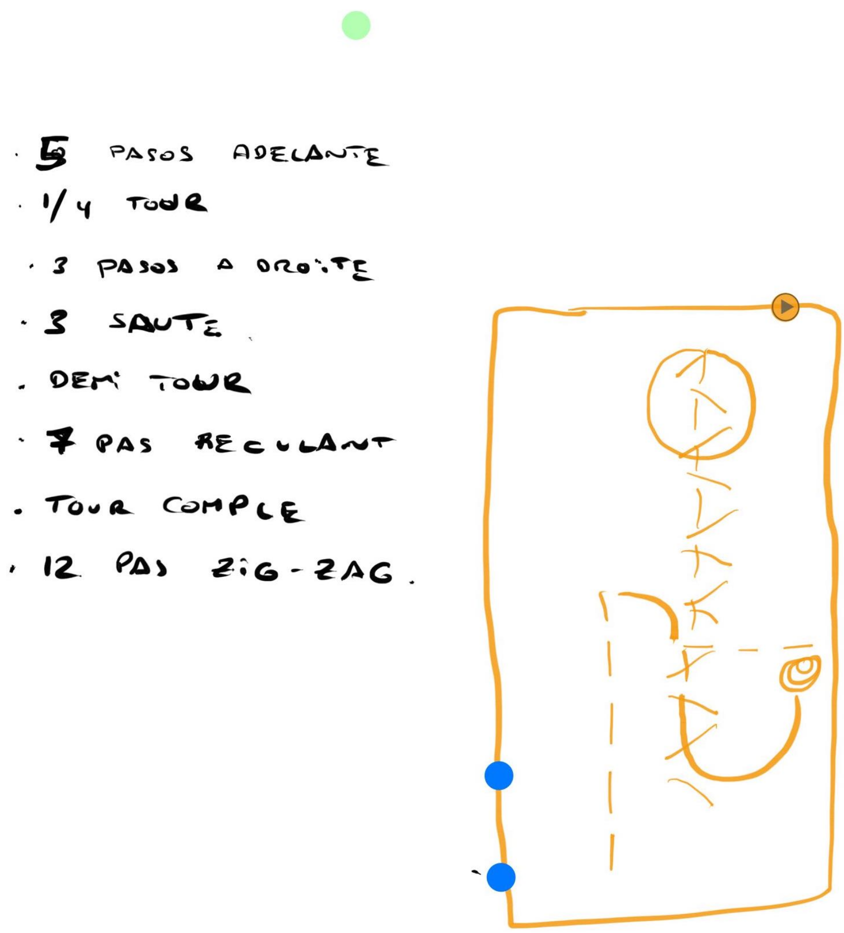

Figure 85: Residency: P2 and P3 represented their part in a floorplan and added textual explanations of the main actions.

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COLOPHON

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ÉCOLE DOCTORALE
Sciences et technologies de l'information et de la communication (STIC)

Titre : Supporter la pratique créative experte

Mots clés : chorégraphie, graphisme, créativité, interaction humain machine

Résumé : Cette thèse porte sur la conception d'outils numériques interactifs pour les professionnels du design graphique et de la chorégraphie contemporaine. Ces praticiens utilisent des principes et des méthodes personnels qui contraignent et guident leur processus créatif. Je soutiens que, pour construire des logiciels puissants permettant d'étayer leur pratiques, nous devons les laisser définir et manipuler leur propre ensemble de *contraintes créatives*. Je présente deux outils qui illustrent cette approche. *StickyLines* offre des représentations visuelles des contraintes d'alignement et de distribution d'objets graphiques afin de mieux répondre aux besoins des utilisateurs. *Knotation* permet aux chorégraphes d'esquisser leurs idées et de les rendre interactives, en leur permettant de représenter des *contraintes*, du *mouvement* ou une combinaison. Je montre que, bien que leur produit créatif soit de nature fondamentalement différente, le processus créatif de ces professionnels peut être abordé avec une stratégie commune: permettre aux utilisateurs de créer des *substrats* interactifs qui articulent *contenu* et *contraintes*.

Title: Supporting expert creative practice

Keywords: choreography, graphic design, creativity, human computer interaction

Abstract: This thesis focuses on the design of interactive digital tools for professionals in graphic design and contemporary choreography. These practitioners employ personal principles and methods that constrain and guide their creative process. I argue that to build powerful software tools to support their practice, we need to let them interactively define and manipulate their own set of *creative constraints*. I introduce two tools that illustrate this approach. *StickyLines* provides visual representations of alignment and distribution constraints in layout design to better match users' needs. *Knotation* allows choreographers to sketch their ideas and make them interactive, letting them represent constraints, movement, or a combination. I show that although their creative product is fundamentally different in nature, these professionals' creative process can be addressed with a common strategy: Allowing users to create interactive *substrates* that articulate *content* and *constraints*.

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