ABSTRACT
This paper aims to broaden the understanding of computer mediated creativity from a material perspective, by emphasizing the qualities of resistance and making users' actions explicit in the design process. Resistance of material refers to the challenging nature of realizing one's intention through material during the design process. Materials are also instrumental in making user actions of creating artifacts explicit through temporary structures, residues and tools. By drawing on the accounts of craftwork and design, the paper discusses how these two qualities can be deliberately addressed in the design of tools to support creative activity. The design approach is operationalized in a 3D drawing tool with the use of indirect control to control curves. The prototype was evaluated with industrial design students and practitioners in two stages, in recorded sessions and through self-documentation. The participant responses give insights into the concept of materiality in creativity support tools and in which cases these features were embraced or dismissed.

Author Keywords
Material; material engagement; 3D modeling; drawing; indirect control; design; craft

ACM Classification Keywords
H.5.2 Information interfaces and presentation – User Interfaces; H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design

INTRODUCTION
In design practice, interaction with digital tools is regarded as a part of the creative process. For many cases the expected output, in the form of a 2D drawing, 3D model or other format, is not precisely defined; the design goes through major changes or refinements throughout the use of the digital tool. Related to this observation is the HCI community's interest in supporting creative process through the design of digital tools [17, 26, 27, 31]. This paper offers an understanding of supporting creative activity through digital tools from a material perspective, by providing insights into the role of certain material qualities in form-giving.

The paper focuses on designing digital tools regarding two aspects of materials. First, the designer's direct engagement with material often yields to unexpected outcomes, partly as a result of material qualities and what can be called resistance of material. As remarked by various scholars, the rationalist account of form-giving as realizing a preconceived form through material gives an insufficient account of form-giving and design. Ingold [9] states that creative activity involves “following the materials” as opposed to the “imposition of form upon material world” by a human agent. In the field of design, Schön’s idea of a “reflective conversation with the material” [22] is widely acknowledged. These reflections on the creative process identify materiality as one aspect that yields to previously undetermined outcomes as the design process unfolds. At the same time, in order to identify the priorities for designing digital tools with this purpose, further elaboration on materials and digital tools is needed regarding their capacity to yield unexpected results. Practitioners of design and craft have traditionally been sensitive to different ways various materials and activities affect the form-giving process. This sensitivity has been reflected in the preference of certain materials and activities over others, pointing to different expectations of material.

In addition to facilitating unexpected outcomes, materials provide hints of the actions carried out during the process of creation. The spatial presence and multi-model features contribute to making the human agency explicit [11]. Designers’ use of materials involves the use of material for persuasion and narration in collective creativity [11]. In some cases, such material evidence is embedded in artifacts as “material traces of skill” [21].
Research on creativity regards such aspects of materials mostly as undevised, emergent qualities and focuses on existing physical materials or software with few studies aiming at designing digital tools to deliberately address these aspects. This paper asks if such a pursuit is viable in the design of tools to support creative activity, by reporting from a design case of a 3D modeling tool for drawing curves. The study involved early ideation and design phases followed by a two-stage user evaluation.

BACKGROUND

Materials in Design

The question of material and how it can be defined in relation to digital technologies has been an area of concern for the HCI community. A body of work has been conducted on how physical materials are integrated into creative practice and the design of digital technologies from a material perspective. In the field of interaction design [28] extend the concept of agency, traditionally reserved for humans, to interaction design materials and demonstrate how material agency emerges during short prototyping sessions in groups. Their case involves the early design phase and shows how material qualities contribute to the conception of interactive artifacts. In another study on architectural design, [11] show the use of materials as communicative resources in collaborative settings. An important concept they emphasize is the designers’ skillful use of materials as communicative resources, yielding to performative acts.

Apart from these studies that focus on the role of existing physical materials and practices to inform design, a body of research treats computer artifacts as material. Studies on the practice of engineering drawing [8,24] analyze the different practices while working with traditional paper and CAD software to create technical representations. Engineers and draftsmen work with their drawings through specific materialities the interface offers. At times the drawing interface itself turns into the object of attention.

The comparison of physical materials and digital technologies has been a matter of debate, since the digital material lacks intrinsic qualities in the same sense that the physical materials do [14]. Still, the notion of material qualities is pronounced in relation to computing [30] and sensor networks [25]. [30] is concerned with designing computer artifacts analogous to shaping physical artifacts and propose composite materials using both computational and physical properties. While they regard computation in general as material and refer to the general qualities of computation such as temporality and reversibility, a body of work [2, 17] has investigated the qualities of specific software as a material for designers. This is also the approach in this paper; the focus is on the particular features of the prototype developed during the design process.

Resistance in Material and Craft

Directly engaging with physical materials has been valued by craftspeople as an integral part of the form-giving process. An important aspect of direct engagement with physical materials is what might be called the resistance of material, implying the challenging nature of realizing one’s intention. This aspect was voiced especially by craftspeople and artists at the beginning of the 20th century [29]. Resistance in materials was linked to a certain ideal of form and was contrasted with other forms of making such as painting. As historian Tillyard states, “The bare bones, the nakedness and the restraint of craft were contrasted with the superfluity and thus the superfluousness and superficiality of contemporary painting” [29: 30]. An example of the elevation of manual work at the expense of sketching was the approach of “direct carving” [32] in sculpture. This approach implied that sculptors should be personally engaged with the sculpting material, without making preliminary sketches or models and should realize their intention through the “arduous task of carving” [32]. The carved out material was contrasted with sketching and the malleability of cast material. Unlike modeling, sculptors embracing the approach of direct carving started their process with an initial body of material volume. Making of the sculpture in this case was not viewed as an execution of a preconceived idea, but as an open-ended process driven by the qualities of material.

Similar views have been expressed in relation to digital tools. [2] consider materiality as a key aspect of computer mediated musical composition. Based on their interviews with composers, they show how the functional elements of the music generation software construct the “resistance of the material”, as they call it, which they regard as a necessary premise for creative activity. At the same time, qualities such as resistance need to be reassessed when transferred into activities such as programming or 3D modeling using computers, since material qualities such as hardness or plasticity are not easily mapped to digital tools.

Theoretical work on handwork and craft abstract a few concepts that reflect on the concept of direct engagement with physical materials. Dormer [4] acknowledges the tension between maintaining a static intention and the “inevitable vagaries” of craft work, and regards “virtue of a conflict” as a positive component of craft work. A loosely related term is “workmanship of risk” by Pye [18], associated with handwork. Pye characterizes workmanship of risk by the uncertainty of the outcome regarding quality. From this perspective, 3D modeling practice also involves risks since the quality of the model is not predetermined and requires effort and care to model. Yet, as [16] note, digital material and digital craft bear little risk in comparison to physical material, particularly due to the functions “undo” and “save as”. Furthermore, as Pye notes, workmanship of risk in its pure form is hard to find and craftspeople often employ material aids such as rulers or compasses that reduce the risk associated with handwork.
Digital Tools and Supporting Creative Activity
3D drawing applications as a material support a few features that can be considered as aids that structure user input, such as snapping to grid and geometrical constraints. A widely adopted feature of most vector drawing programs is the “control point” construction to control freeform curves, known as splines. In this model, a curve is generated to follow a set of control points optimally and the user control of the curve is through manipulating the control points. Based on the principles of Bézier curves this construction model became popular since it avoids any “undesirable, historically vexing, extraneous shape undulations” [3]. In this regard, the digital spline is much like the earlier wooden spline that uses the stiffness and flexibility of wood to achieve the most optimal curve passing through a number of points [5].

Including aids in virtual drawing space has also been proposed to support drawing activity. Few studies use virtual instruments for modification and as constraints, avoiding the traditional method of using control points. [19] proposes including stick shaped tools for various functions such as carving out, aligning or scaling drawings in 2D design space. HabilisDraw [23] offers similar functionality and uses objects like compass, ruler and pen as drawing constraints in 2D virtual space. Virtual tools in these examples can be related to the concept of “interaction instruments” [1] that are reified in the interface and operate on the objects of interest (user’s drawing for the mentioned examples).

The design approach of the drawing tool is specifically aimed to recreate the qualities of materials that facilitate resistance and unexpected outcomes. Supporting creativity, in the sense craftspeople regard material, necessitates a broad understanding of designing software features, potentially incorporating aspects such as resistance and effort. In this case, the assumption of users not having a completely predetermined design idea also implies that the design can be negotiated through the interaction with software, in a dialogue with the material. The design approach of the drawing tool is specifically aimed to recreate the qualities of materials that facilitate resistance and unexpected outcomes.

Indirect Control
One design consideration was to facilitate the tension between the user’s intention and the response of material in the process. The fact that materials challenge the designers in reaching their intentions is recognized in design. The traditional method of controlling curves through control points is direct and gives designers an expected and precise response to their actions. In comparison, thinking in terms of resistance and unexpected outcomes facilitated by the materials behavior gives the designer an opportunity to experiment with forms of controlling the 3D model that are less precise and unpredictable. These qualities are not inherent in digital tools but can nevertheless be recreated. This design approach is based on the preference of designers and craftspeople to directly engage with materials to maintain an open ended process.

Making Actions Explicit in the Workspace
One possible design implication of treating 3D models as an outcome of user’s actions with material is visualizing the effort of 3D modeling in the workspace. Conventional 3D modeling applications display the model in design space, giving little account of the process of modeling. Although the user operation history can be accessed through
interface, such engagement is not direct and is mostly used for error correction. Physical materials, in contrast, provide traces of actions carried out by the designer through multiple ways. [11] note how the residues of a carved out material block are significant in showing the action carried out. As they put, “These leftovers do not simply disappear (unless put into a bin), they witness some of the action that has been taken and the design decisions that motivated it.” [11]. Materials like residues do not directly represent the finished work, yet still communicate the material history of a design artifact by emphasizing the notion of carving out.

Compared to supporting creative activity by history functions accessed through menus, such objects in the work space show how the user’s history can be visualized in the form of temporary structures, tools or leftovers. These objects, spatially located in the modeling space, have the potential to reveal how the designer has worked with the digital material throughout the creative process.

THE PROTOTYPE
After an initial ideation phase, a prototype, named kfields, was designed as a plug-in for a vector based 3D modeling program, Rhinoceros. The prototype was specifically designed to draw curves. The fundamental idea was to control curves indirectly through objects in design space. The user was unable to change the curve through control points, but had to use the manipulative elements in the design space to control the curves. In modeling software, applications for physical simulation and parametric modeling enable using other objects (named attractor points or attractor lines) to modify curves indirectly. Similarly, the prototype developed for the process enabled parametrical manipulation, simply by building objects in the design space. The concept was conceived as an alternative way of controlling curves and, unlike generative modeling software, required no programming or any additional scripting interface. Rather than drawing a curve at once, users would first determine end points and then create “pull” and “push” elements in the modeling space to create fields that indirectly modify the curve shape.

Figure 1. A curve modified by “pull” elements (right) compared to the regular representation of curves (left).

The prototype also allowed grouping objects in different layers; manipulative objects would only modify the geometry in the same layer. All the interaction with the objects was based on scaling, rotating and moving the manipulative elements and dragging the curve end points in the modeling space.

In the first stage of the user evaluation the prototype only allowed the modification of a preset geometry; participants were unable to add new objects. In this stage, participants were able to see ambient curves that indicate the overall field of effect created by the manipulative elements. Additionally, a sphere inside a torus shape represented the total mass of all manipulative elements in the modeling space.

Based on the feedback gained from the first stage, a prototype was created for the second stage. This prototype enabled creating new geometry objects and also declaring any shape as a manipulative element. This function was implemented to see if the participants would be sensitive to how manipulative elements are represented in the modeling space. Additionally, the prototype featured the function of “neutralizing” curves, turning them into normal curves that can be controlled by control points but are no longer manipulated by any pull and push element.

The prototype operationalized the notion of indirect control by making the exact control of curves harder and generating unintended outcomes by controlling more than one curve. Due to the lack of control point adjusting, the users were unable to precisely draw curves, but had to rely on manipulating elements. A second aspect of using manipulating elements was the reification of users’ modifications on the curves in the form of “pull” and “push” elements. These elements remained in the modeling space, unless manually hidden, and indicated how the curves are modified. Their shape and scale could be determined by the user, and their dimensions represented their force in different axes.

THE USER EVALUATION METHOD
User evaluation of the prototype involved two stages. In the first stage a limited prototype was tested individually with 4 participants in sessions ranging from 25 to 45 minutes. The composition of the participants at this stage was 2 industrial design practitioners, one design student and one makerspace runner. The prototype featured basic functions of the design idea.
The concept and basic functions of the prototype were briefly introduced to the participants before the actual sessions began. During the sessions participants were encouraged to think aloud, ask questions and make comments about the prototype. Participants’ interaction with the prototype was screen-captured and after each prototyping session, participants were interviewed to get further insights and ideas.

In the second stage the prototype was used in the work environments of 6 participants. Among the 6 participants, only one had participated in the first stage. The composition of the participants was 4 industrial design practitioners and 2 students. In the second stage of the user evaluation, the emphasis was on the personal context of using the prototype. The prototype, downloaded by participants, was functional enough to be used independently. The participants were not given a specific task, but were rather asked to model their ongoing design task or any other design of their choice using the prototype.

In addition to the prototype, users downloaded a manual that explained the functions of the prototype and a template document to report their experience of using the prototype. Self-documentation methods such as diaries and probes are used in design to get-in-situ information from participants, mostly in order to evaluate novel products or get insights for future products. Similarly, the text editor file used in the study included “situation” definitions in which users could fill in comments and insert screen-capture pictures of their modeling spaces while working with the prototype. As the main task of the participants was to experience the prototype, the self reporting activity mostly functioned as a diary intended to capture an ongoing activity [20]. Yet, various situation definitions were created to stimulate participants’ thoughts, as in the case of probes [6, 15], and some participants tried to fill in all the situation definitions. Situation definitions captured possible shifts in design and tensions between the user’s intention and the outcome of his or her actions. The selected situation definitions were:

- Register a moment which made you say I am thinking hard on how to model my design with the prototype.
- Register a moment which made you say I declared my own shapes for the Pull and Push elements.
- Register a moment which made you say I ended up in a design I initially did not plan to model.
- Register a moment which made you say It was hard to model my idea with the prototype but I am pleased with the result.
- Register a moment which made you say At this moment it is really frustrating to work with the prototype because of THIS.
- Register a moment which made you say I changed my direction about the form / idea I am modeling.
- Register a moment which made you say At this moment I switch back to normal curves because of THIS.
- Register a moment which made you say I wish the prototype had THIS functionality.

In addition to these situation definitions, users were able to create their own situation definition in a reserved slot. Participants emailed the diaries they had been keeping after a time period of between 5 days to 2 weeks, depending on the schedule of the participant.

After participants submitted their diaries, they were remotely interviewed to get further comments and to elicit the material in the diaries.

RESULTS
This section summarizes the results of the two user evaluation stages related to form-finding, predictability, and indirect control elements. Notations “S1” and “S2” refer to the first and second user evaluation stages respectively.

Control and Predictability
Participants, in general, stated that it is hard to predict the behavior of the program. One participant noted that he was not able to control the curves precisely. He also stated that at times the program takes command and behaves unpredictably.

“I can’t think of a single occasion where the end result could be planned beforehand unless you have some sort of embedded physics engine in your brain…” (Participant E, S2)

“It is too much surprise, it should be more conscious, it is leaving my work to the program, and the curve explodes, it becomes something bizarre.” (Participant A, S2)

At some points the participants distinguished between what they would like to control and what would rather leave to the prototype.

“I would probably like to have those points (end points) not to be distorted at all. I would probably have dimensions that I have as reference, dimensions from one end to another and be searching the form in-between.” (Participant K, S2)
One participant noted that he struggled to achieve a 10 mm buckle from the middle of the curve, yet was not able to achieve this exactly because of the indirect control. He registered this in his diary by annotating the curve with the dimension, 10,15.

On the other hand, participants saw benefits of not being able to directly individually control curves.

“I use f10 (control points for modifying curves) quite a lot, but I distort the continuity of curve while doing it. I liked the continuity in indirect control. But I should be able to set dimensions, or I should be able guess where the curve will end up.” (Participant A, S2)

“I think it creates a cleaner surface when compared to the built-in commands... It does not stretch the form too much and distort its smoothness.” (Participant K, S2)

“...Actually it is good if you are not making something very specific, if you are working on surfaces, it is a much better solution. Because for that (manually controlling the curves), every control point you add makes the form more complicated and as it gets more complicated it tends to be more awkward...” (Participant R, S1)

Universal control of the curves in design space was another feature that was considered challenging by the participants. Participants in some cases expressed their dissatisfaction with the mechanics of the prototype which modifies all the curves in the layer when trying to adjust only one curve.

Instead of using different manipulation layers, one participant solved the problem by turning each of the curves into normal curves, thus making them unresponsive to manipulative elements.

“My biggest problem was distorting one curve, while trying to modify another, I guess for this you created a command called like “neutralize”; it turns it into a normal curve... I used that, but after some time it just became too laborious to use it on each curve that I drew...” (Participant A, S2)

“I think you don’t necessarily need to modify all at the same time to achieve visual coherency. It can be implemented, like modifying the curves evenly...It should be up to the user to determine which element will modify another element, but the effect of elements should be determined by the program itself.” (Participant L, S2)

Ease of Form Exploration

Participants were generally positive towards the ability of the prototype to easily edit geometries. In some cases participants reformulated their role as “picking up” from possibilities or “analyzing” rather than modeling.

“...It is a bit like the program is making the design for you, but it is ok. You can easily create the curves that would end up in the forms you like... it does not design exactly but offers possibilities and you pick.” (Participant A, S2)

This was voiced in the cases that involve controlling more than one curve; participants registered that indirect controlling through manipulative elements eased the process.
beyond modeling would be intrusive. Participants in some cases expressed specific uses such as animation or form-finding for a specific location (as in the example of a building) or form-finding for a logo. In addition to these uses, one participant associated the mechanics of the prototype with a specific designer (Ross Lovegrove) because of the “surface continuity” and the “softness in transitions”. Functional qualities also played a role; a participant associated the prototype with “bowl and basket like forms”, “forms with wings” that are “U shaped forms with angles”. Technically, the prototype was capable of making curves with fixed points at both ends, but it was not possible to join them continuously, so ‘U shaped forms are related to this functional limitation.

**DISCUSSION**
Designing digital tools embraces certain assumptions on what is integral to creative activity and what is seen as tedious work, effort spent on externalizing design mostly seen as a tedious task. Yet, this distinction needs to be elaborated, especially from the viewpoint of craft and design which acknowledge effort spent with material as an integral part of creative work. The goal of the study is to make the effort spent during the interaction with software itself meaningful as a creative activity, in contrast to the design ideal of software as a disappearing tool. The design objective is not to decrease the amount of effort spent on using the software but rather to make the engagement with the software meaningful.

**Material and control**
Most sculptors embracing the approach of direct carving shared a respect for material, emphasizing the inherent qualities and constraints of the material [32]. Yet, such a commitment from users to the intrinsic qualities of the material cannot be taken for granted. Unlike natural materials like stone and wood, the qualities of synthetic materials and software can be negotiated in terms of built-in functions. The user study helped identify in which instances the participants were committed to the specific qualities of the prototype and in which instances they considered them as functional limitations. Although the participants did not register big shifts in their designs while using the prototype, the tension between user intention and the material behavior emerged in the level of control.

In the interviews, participants stated that the prototype they were using did not enable precise manipulation of elements and registered moments in which the response from the program was unexpected. At the same time, not being able to control the elements directly was related to the ease of achieving continuous curves, since indirect control decreased the risk of distorting the curve. Exact control and curve smoothness in such cases seem to be contrary and handing over some control to the software was identified as a good quality by some participants. In these cases, the participants implied that the smooth and visually pleasing qualities of the curves were an intrinsic feature of drawing curves with the prototype.

Yet, some cases were perceived as functional limitations and participants expressed what they felt missing, such as being unable to join curves. In these cases the participants evaluated the prototype in terms of functional limitations rather than accepting it as an intrinsic quality of digital material. Participants’ feedback implied that loss of control in such instances was different from the loss of control when modifying the curves by manipulative elements and once they understood that their intended action is not possible to implement they disengaged themselves from the activity. In such moments the feeling of material with intrinsic qualities broke up and participants evaluated the prototype in terms of its technical constraints. This observation is similar to Laurel’s characterization of good constraints in interactive fantasy worlds: “The user respects the limits of a mimetic world by refraining from introducing new potential into it” [13: 104]. Although the study did not target real world likeness, it is important to pay attention to the cases in which the qualities of digital material are respected or found insufficient.
The experience of resistance and functional limitations is related to the design case and intention of the user. Few user responses show cases in which the resistance was most strongly felt such as trying to model with exact numerical numbers. In other, more open ended tasks the feeling of resistance was not as strong.

Making Actions Explicit through Material

The prototype developed during the study made particular material qualities explicit by causing unexpected outcomes and containing control elements in the modeling space. Such manifestations in turn make the effort spent on the modeling activity evident, by embodying the user’s actions in the form manipulative objects.

The HCI literature is rich with examples that support creative work through user workflow history management, visualizing the previous state of documents and a user’s actions. In contrast, rather than relying on user history, the prototype described in this paper demonstrated how the user’s actions can be reified in the form of manipulation objects, similar to traces of human agency on physical materials in the form of tools and residues. Visual programming interfaces enable extending the user interface by reifying user commands in the form of visual programming objects [2]. The prototype developed during the study similarly enabled reifying the user’s actions. Additionally, placing the users in the same visual space with the design work resulted in heterogeneous 3D workspaces that contain both the manipulation objects and the actual design work.

This juxtaposition of the end work and the user’s actions show how the universal construction of digital material such as surfaces and splines curves can be reconfigured to give an account of the specific materialities of different software. For example, curves in the prototype are not curves as such but are pulled or pushed by manipulative elements. They act as annotations of the actual design, revealing the intentions of the designer.

User evaluation shows that these qualities were considered useful in some instances. Although the user study did not involve any collaborative setting, participants indicated that inclusion of indicator and control elements in the modeling space can emphasize the notions of flow.

At the same time, the user evaluation signaled that the presence of elements such as manipulation objects in the workspace is only partially accepted by designers. These elements do not belong to the actual design work and participants in some cases expressed that they find the presence of control elements in the modeling space intrusive since they occlude the actual design and that they would be better not included in their presentations.

CONCLUSION

Through reflections of material and handwork, the paper identified how the emphasis on materials in the design process can broaden the design approach for digital tools. This was informed by the less emphasized qualities of materials and handwork such as resistance and contingency and the potential of materials in rendering the actions carried out during the process of creation visible. Together, these qualities stress the significance of engagement with materials as an integral component of creative activity. The paper analyzed how these call for a reconsideration of the design ideals related to supporting creative activity, concerning how the creative work is controlled and represented through the interface. In the study, these ideas were embodied in the indirect control of geometry and the heterogeneous workspace that includes objects other than the end work. At the same time, user evaluation shows that the acceptance of these features cannot be taken for granted. In assessing creative interfaces, it is crucial to identify the cases in which the various features of the tool are embraced as inherent qualities or dismissed as functional constraints. The distinction between what is perceived as material quality and what is perceived as functional limitation was dynamic and dependent on the individual case of design.

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