Haptixel: Enabling Object and Data Physicalization through a DIY Wearable Unit for Pressure-based Encountered-Type Fingertip Haptics

Elodie Bouzbib, Louis Badr, Claudio Pacchierotti, and Anatole Lécuyer

***Abstract*—Virtual Reality (VR) or Augmented Reality (AR) enable the visualization and exploration of content, by augmenting a 2D rendering through a depth perception. In this paper, we investigate how to augment this depth perception by leveraging fingertips haptics. We propose Haptixel, a lightweight DIY encountered-type wearable unit, providing on-demand force-feedback on the users' fingertips' pulp. Haptixel translates digital information into pressure and force-based haptics as if they were physicalized pixels. Haptixel is servoed in force and we conducted a technical evaluation showing that Haptixel has an accuracy of 0.04 N. We also characterized the effect of finger support material (rigid, flexible) on the users' force perception, and eventually quantified Haptixel's Just Noticeable Difference (JND) to be around 0.6 (Weber fraction). We propose a design space for Haptixel, where Haptixel can be used to provide feedback with any visual support, through different force levels and contact types; conveying *in-hand* and *off-hand* exploration properties, whether inherent from the digital environment or to interpret as an encrypted pattern. We illustrate our design space through a user evaluation (n = 16); we show that participants can significantly discriminate at least four levels of forces (+ no contact) with a 0.34 N global accuracy in a VR pixel art-like application - where participants drew the physical patterns they perceived over blank canvas. We finally propose a set of use-cases with Haptixel, including virtual and augmented object manipulation, data exploration and manipulation, urban planning, navigation guidance or piano mentoring.**

***Index Terms*—Wearable haptics, Data physicalization, Virtual reality, Haptics, Encountered-type haptics**

I. INTRODUCTION

WITH the burst of VR and AR technologies, a need for immersion through the involvement of the entire body is perceived. More specifically, the integration of haptics - the sense of touch - is currently a timely topic, mainly for 3D object exploration and manipulation, social interactions or immersive analytics.

Many haptic technologies are being developed in these regards, whether to provide control over a virtual environment or a better understanding of the user's surroundings. However, digital content whether on 2D screens or without visual support can also be leveraged and augmented through haptics, providing a *depth* perception and therefore a third dimension.

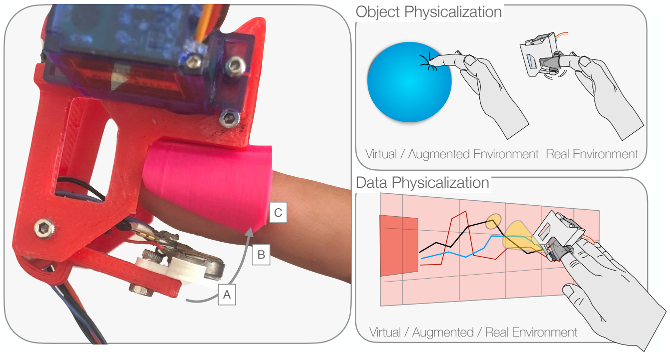

Fig. 1. (Left) Haptixel consists in a lightweight DIY wearable unit, (A) leaving the fingertip free and (B) encountering the users fingertip pulp to provide low or (C) high levels of forces (and vibrations); with proximity and force sensing. Its concept relies on force discrimination and allows for a physical depth perception of digital content, e.g. physicalized pixels. Its capabilities allow for (Right - Top) Object physicalisation, for instance a user can perceive contact / stiffness of a virtual/augmented object in such environments; but also (Right - Bottom) Data Physicalization, to translate physically graph information or to convey additional dimensions.

In this paper, we focus on this physical depth and translate it into a mechanical requirement to provide different levels of force and pressure, as *pixels*, to the user's fingertips. The fingertips are the most sensitive part of the body - and our primary medium of interaction. While force-feedback is at the center of many haptic technologies [1], enabling the users to discriminate various levels of force-feedback through their fingertips is under-explored.

In order to keep the users' untethered and free to interact within the environment, we designed a DIY and open-source wearable unit called Haptixel, which encounters the users' fingertips pulp only when an interaction is required [2], [3]. Haptixel is a lightweight wearable (19g) with high modularity: it is equipped with both proximity and force sensing, provides up to 5N force thanks to a crank-rod mechanism and also contains a vibration motor to expand its interaction capabilities. To adapt to any finger size and to cater for the fingerpad local deformation after contact, Haptixel is servoed in force. We propose a model to instantiate force-servoing and conducted a technical evaluation showing a 0.04 N accuracy and a latency to destination under 1.5s over four different levels of forces. Haptixel provides force and pressures through skin deformation. We thus designed two types of

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finger support: rigid and flexible. We evaluated the impact of the printing material on the users' force perception, and quantified Haptixel's *Just-Noticeable Difference* (JND) to be around 0.6 (Weber fraction).

We propose a design space for Haptixel, through six dimensions: (1) *visual support*; (2) *force levels* and (3) *contact types*; (4) *in-hand exploration properties* - which we define as properties that can be perceived through a direct exploration or manipulation and relying on absolute forces; and (5) *off-hand exploration properties* - being conveyed from a hovering distance and relying on more relative forces; and (6) *stimulus interpretation* - as Haptixel can be used to represent **substantial** information, being straight-forward for the user to interpret; or **abstract** information, through embodiment [4] or pattern encryption.

We illustrate our design space in a user evaluation, where we empirically assessed Haptixel's ability to provide absolute and relative levels of force without visual bias. Participants were asked to hover on top of a blank pixel-art canvas to perceive different forces; and were asked to replicate the patterns they felt as if the canvas was a heat map. The colors and heights indicated their perception of forces and therefore the depth of the drawing, and we showed a 0.34N global accuracy in the absolute force discrimination; and a really accurate replication of the given patterns. There was also a significant effect on force discrimination, showing that participants can perceive at least four different force levels using Haptixel.

Finally, we propose a set of cases for Haptixel, where it can be used for the (a) exploration of 2D content with depth perception (e.g. geographical maps); (b) direct manipulation of 3D content with haptic features (e.g. piano keys with different levels of forces and stiffness) or (c) to perceive external feedback (navigation guidance, morse code).

Our main contributions are:

- Haptixel, a novel DIY encountered-type wearable device providing pressure and force-based haptics on the fingertips pulp with various levels of forces;
- Empirical results showing the finger support material effect on users' JNDs (Just Noticeable Differences);
- A model to instantiate force servoing and a technical evaluation comparing servoing methods;
- A six-dimension design space involving Haptixel, with in- and off-hand exploration properties as well as both substantial and abstract stimulus interpretation;
- Empirical results showing Haptixel's efficiency in a blind depth/force discrimination task, replicated through a pixel-art like application.

II. RELATED WORK

A. Fingertip Stimulation Factors

The hand and more specifically the fingertips are the most sensitive parts of the body. They represent the main communication medium with a user's physical vicinity; and therefore have been at the center of many stimulation devices for exploring and manipulating augmented or virtual environments. However, many properties are to consider when designing fingertip haptics.

First, the fingertip is sensitive to contact; and we believe that its perception should benefit from the "encountered-type haptic device" concept [2], [3]: letting the users' fingertips unencumbered when no interaction is required, and encountering it when needed. This concept has been integrated with controllers [5], [6] or exoskeletons [7]; but can also be miniaturized in fingertip devices [8]. For instance, this can be performed by either rolling around the user's finger to provide contact perception [9], by *auto-gripping* the user's fingertip when required using proximity sensing [10].

Second, the fingertip/interface contact area alters the user's perception of compliance (and other object mechanical properties) [11]; as well as its restriction among the device [12]. Moreover, the fingertip size can also alter the perception using a same device [13]. It is therefore important to design for a wide range of finger sizes, and to account for the finger restriction within the worn device.

Third, and apart from users' fingertip perception, many design considerations regarding the devices themselves exist: size, weight, inertia, not interfering with dexterity [10], [14].

Fourth, when interacting in the real world; most of our haptic rendering consists in contact perception, and pressure applied over the fingertips (e.g. writing on a keyboard). However, currently many wearable haptics rely on vibrations to provide information [15]. We believe that choosing a pressure and force-based feedback could replicate the real environment interaction properties more intuitively [16].

In this paper, we account for all the above through a pressure and force-based wearable encountered-type haptic device. Its main difference from the literature is to encounter the fingertip and provides various *types of contact* and *levels of forces*. We also propose a method to adapt to many finger sizes; and quantify the fingertip restriction impact on force perception.

B. Object Exploration and Physicalization

Many haptic devices (wearable or not) are being used to simulate objects for users to grasp, explore, manipulate in AR or VR.

This physicalization is done by replicating objects' inherent properties, such as impact when touching [17]–[19]; texture perception [18], [20], [21] when users perform a lateral motion; local shape discrimination [22]–[25] when users follow objects' contour; global shape [26]–[29] when users enclose the objects within their fingers and perform grasps. Other properties include stiffness [30], [31] or weight [32]; when users either lift objects or press them. Some devices even combine stimuli to extend their interaction design space (e.g. touch, slide, textures [19]).

While all of these papers demonstrate the use of devices or strategies to provide haptic feedback, they all rely on the visual support in which they are being used. Though, as per Teng and Lopes [33], it is important to start designing for haptics outside of AR and VR; without relying on these visual supports. Haptics can indeed be used to provide these environments with substantial properties; but can also be used for interpreting information in the outside world.

C. Data Exploration and Physicalization

Data physicalization refers to "physical artefact whose geometry encode data" [34] and can be represented through shape-changing devices such as 2.5D interfaces using pins [35], fluid haptics [36], tangibles [37], [38] or even VR controllers [39]. Many data exploration properties can be perceived through haptics: bar chart can be manipulated *in-hand* [37]; densities or intensities can be explored [39]; and changes made by collaborators can be physically perceived. It also has the benefit of adding another dimension to a chart: a 2D geographical map's depth could for instance be felt when hovering on top of it. Similarly, while our current GPS and navigation devices provide 2D information, haptics could leverage depth, or height, at a personal and finger scale.

Some miniaturization was performed on 2.5D interfaces, becoming controllers users can hold (such as PoCoPo [25] or Texture Touch [23]) - though these have only been used to render object properties and have not explored other physicalization dimensions. In a recent Data physicalization survey [4], tangibles and shape-changing devices are being used, while wearable haptics are still not integrated. Also, multimodal interaction are considered for data exploration [40] - through touch in screens, or interaction techniques involving pens. However, the integration of active haptics to embody and convey data information physically is still under-explored.

In our paper, we focus on providing different levels of force-feedback and pressures in a wearable unit; while the concept is not new, the design space Haptixel covers include both object and data physicalization; and we aim to embody and convey both substantial inherent properties as much as abstract ones.

III. IMPLEMENTATION

To design Haptixel, we considered multiple criteria from [14]: weight, form factor (size), wearability; and focused on providing adequate feedback with low inertia, high haptic transparency, low cost in a DIY self-contained design.

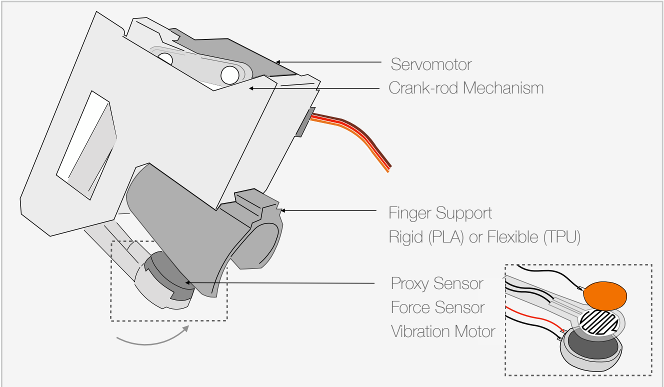

Fig. 2. Schematic of Haptixel's mechanism: the device consists in a crank-rod mechanism integrated into a small lightweight wearable unit. Haptixel's actuation brings a lever to encounter the user's fingertip pulp. Call-out show Haptixel's end-effector: a proxy sensor, on top of a force sensor, on top of a vibration motor.

A. Hardware

Haptixel consists in a 3D printed crank-rod mechanism, encountering the fingertip pulp. Haptixel's weighs 19.8 g and measures $40 \times 40 \times 45mm^3$. Haptixel's design is open-source and available on the following[1]. Its printed parts weigh 9g in total, and it can be printed in its entirety in 1h50 minutes.

1) Actuation: Haptixel is actuated through a Feetech FS90 servomotor, with a weight of $9g$ and a torque of $1.5kg.cm^{-1}$. Globally, Haptixel has a 70° stroke, which can therefore interpenetrate the fingertip's pulp with a high force. Apart from its lever concept, Haptixel's end-effector also contains a mini vibration motor (see Figure 2). The servomotor is controlled using a Pololu Micro Maestro board, enabling an easy access to its speed and acceleration.

2) Sensing: On top of its vibration motor, we integrated a 189-5556 FSR pressure force sensor into Haptixel's end-effector - which we plugged as a voltage divider in series with a $10k\Omega$ resistor and a 5V input; and a capacitive sensing sheet - which we plugged as a voltage divider in series with a $1M\Omega$ resistor and a 5V input. The two sensors are then plugged into an Arduino Uno.

3) Hand attachment: Haptixel is dependent of the finger pad deformation as it aims to provide force feedback to the fingertip pulp [9], [12]. The more constrained is the finger pad and its skin stretch and deformation, the higher its stiffness and therefore the higher is the perceived force - with the same device mechanism. We designed a fingertip support and 3D printed it with different materials. When the support was 3D printed as a TPU part (*T*hermoplastic *p*oly*u*rethane, soft flexible printing), it therefore did allow for less constrained finger pad, with a maximum applied force around 3 N. When the support was 3D printed as a PLA part (*P*oly*l*actic *a*cid, rigid solid printing), it could provide up to 5N force feedback as the finger pad skin deformation was highly constrained. We conducted a psychophysical experiment to evaluate the JND (Just-Noticeable Differences) of both PLA and TPU supports (see Section IV) to quantify the material effect on force perception.

4) Tracking: When used in AR/VR, Haptixel does **not** impair the finger tracking (e.g. using the Meta Quest), and can therefore be worn for free hand exploration and manipulation.

B. Software

We chose to servo Haptixel in force and to control it in speed, while instantiating the god-object principle [41]. Because of the FSR force sensor hysteresis and the finger pad deformation after having been touched, Haptixel's position could not be properly assigned. We conducted a technical evaluation in which we demonstrate the non-repeatability of the force sensing when servoed in position or speed (see Section IV).

1) Haptixel motor control: We created a virtual spring between Haptixel's end-effector and a virtual proxy, so Haptixel's speed is proportional to the difference in position between its actual position and the proxy position (see Equation 1).

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[1] Anonymised for Review

This proxy is itself attached to a target position with a spring damper mechanism (Equation 2), and the target position is found as proportional to the error in force (Equation 3) (see Figure 5), as followed:

$$\vec{v}_{Haptixel} = -K_p \times \vec{HP} \tag{1}$$

where $\vec{HP}$ is the position vector from Haptixel to the proxy; k_p the coupling stiffness. k_p is chosen empirically as to minimise the following error between Haptixel and the proxy.

$$\vec{F}_{proxy} = K_f \times \vec{TP} - K_d \times \vec{v}_{proxy} \tag{2}$$

where $\vec{TP}$ is the position vector from the proxy to the target position and v_{proxy} is the proxy velocity.

$$T_{x,y} = T_{x,y} + K_m \times \epsilon(Force) \tag{3}$$

where with $\epsilon = (Force_{command} - Force_{current})$, $T_{x,y}$ is the *unknown* target position, and K_m is a proportional gain.

2) Digital/Virtual coupling: Haptixel is coupled to digital and/or virtual environments using Unity3D. It can be attached to any object to provide contact information by encountering the fingertip pulp; levels of stiffness and deformation, where the force it provides is proportional to the finger penetration within the object boundaries etc (see Section V). Each digital/virtual unit can be perceived as a **pixel** - which Haptixel physically replicates through pressure and force-based haptics. Haptixel instantiates the god-object principle, where a virtual spring is attached between the users' real fingers and the virtual objects boundaries [41]. Therefore, the mechanical displacement of the lever within the users fingertip pulps is proportional to the users' virtual fingers displacements within virtual objects. Haptixel could also benefit from being coupled to visual illusions and pseudo-haptic effects such as [42], [43], to increase the deformation perception.

IV. Technical Evaluation

In this section, we propose to evaluate Haptixel technical capabilities. First, and as mentioned in Section III, we propose to characterize users' Just Noticeable Differences (JND) - as a function of Haptixel's finger support material (rigid or flexible). This JND will also inform us of the theoretical amount of discrete force levels Haptixel can provide. Second, we propose a technical evaluation to optimise Haptixel's displacements; to ensure accurate and precise force renderings with a low latency to destination. We compare different servoing methods and justify our choice for Haptixel's control.

A. JND Characterization

As mentioned previously, pressure can be induced through skin deformation; therefore depending on the finger support we use in Haptixel, force perception and discrimination can be altered. A more solid finger support can provide higher levels of force, though we do not know whether the JND (Just Noticeable Difference) is similar with both materials, or whether these higher levels of forces are proportional to the respective JNDs per material. In this first technical evaluation, we thus propose a psychophysical experiment, to quantify the JNDs per finger support material.

1) Participants & Procedure: We recruited 8 participants (37% women; 3/8) aged from 23 to 34 (average: 26) from our institution. One participant was left-handed. Participants were asked to wear Haptixel on their dominant hand, then to compare various stimuli. We proposed a Latin-square design for both the used material and the order in which stimuli were presented first (e.g. an ascending order, where the comparison stimulus is lower than the reference one; or a descending order, where the comparison stimulus is higher than the reference one), as per the following:

	1st Experiment		2nd Experiment	
User	Material	Order	Material	Order
0 % 4	TPU	Descending	PLA	Ascending
1 % 4	TPU	Ascending	PLA	Descending
2 % 4	PLA	Descending	TPU	Ascending
3 % 4	PLA	Ascending	TPU	Descending

TABLE I
Latin square design for JND study

2) Design, Task & Stimuli: To define the JND, we used the method from [44]: we defined a series of forces to evaluate {0.5, 1.0, 1.5, 2, 2.5}N; which we used as references stimuli and comparison stimuli. We generated all combinations, and the presented stimuli were then chosen randomly, as a succession of "Ascending" and "Descending" orders. For each set of stimulus, participants were stimulated with the Reference stimulus (RS), then with the Comparison stimulus (CS), and then answered the following: *The Comparison stimulus is* ***Higher than*** *(resp. Lower than) or* ***Equal to*** *the Reference stimulus.* As long as the comparison was perceived as higher (resp. lower), other sets of stimulus were generated - with the same Reference and a novel comparison stimulus being:

$$CS_i = \frac{RS - CS_{i-1}}{2} \tag{4}$$

Once the Reference and Comparison stimuli were eventually perceived as equal, we recorded the value for JND as the previous iteration stimulus (e.g. if CS_i is considered as equal, the JND value is CS_{i-1}). The duration of the experiment was therefore not fixed - as it was dependent on the user's performances to discriminate stimuli. The visuals only consisted of the above question, with no other distraction; and participants answered using the keyboard. We used a within-subject design, and the experimental design was: 8 Participants × 5 Reference Stimuli × 4 Comparison Stimuli = 160 Trials, each with various amounts of comparisons.

3) Results:

a) Duration: The experiment duration was longer for TPU (35 minutes, std = 8 minutes) than for the PLA (28 minutes, std = 5 minutes). This can be interpreted as a hint of a better JND for TPU - as it means participants were including more steps in their force discrimination process before affirming the stimuli were equal.

b) JND: There was a significant effect on the chosen Material (F(1,7) = 6.00, $p_{GG} \leq 0.05$). Globally, the JND was significantly smaller for TPU (0.6 N in average) than for PLA (0.73 N) for every tested force. Though, and as per Figure 3, the results for the 0.5 N reference stimulus were quite high;

as for the other values, the JND did grow with the stimulus [45], providing a constant Weber fraction ($Weber = \frac{CS_{JND}}{RS}$, 0.36 for TPU, std = 0.12; 0.41 for PLA, std = 0.09).

c) Ascending vs. Descending: We also studied whether the stimuli order (ascending vs. descending) affected the force discrimination in the JND characterization. There was also a noticeable significant effect on the order in which stimuli were provided (F(1,7) = 6.97, $p_{GG} \leq 0.05$). When the stimuli was ascending (CS lower than RS, and therefore *ascending* to RS), the JNDs as Weber fractions were constant with a really low deviation ($Weber_{TPU-As}$ = 0.33, std = 0.04; $Weber_{PLA-As}$ = 0.40, std = $7e^{-3}$); and showing better results than the global results. The JNDs when the stimuli was descending is significantly higher ($Weber_{TPU-De}$ = 0.49, std = 0.04; $Weber_{PLA-De}$ = 0.70, std = 0.7); therefore verifying our hypothesis that users' force perception can be altered by the order in which stimuli are provided.

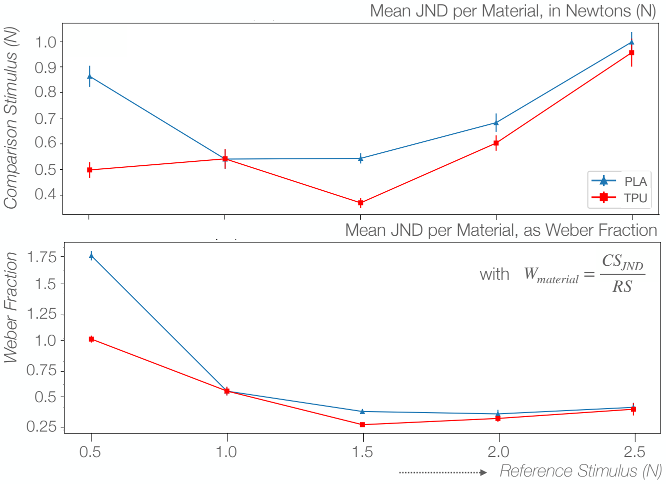


Fig. 3. JND as a function of the Reference Stimulus (N), expressed both in Newtons and in Weber Fraction; for both PLA (rigid) and TPU (flexible) finger supports. Error bars indicate 95-CI.

4) Discussion: In this study, we showed that a flexible finger support can provide higher levels of discrimination, with significantly lower JNDs. In the following, we therefore use the flexible finger support - to provide better levels of discrimination. We also showed that the order in which stimuli are provided can alter the users' perception (JNDs are better when the first stimulus is higher than the comparison stimulus). In the User experience, we will thus explore if users can still perceive relative forces adequately using Haptixel, even in an exploratory task, where the neighbouring forces are sometimes stronger than the current stimulus. We believe that providing a more *continuous* stimulus should cater for this finding and should not reduce Haptixel's capabilities.

B. Position, Speed and Force Servoing

Haptixel relies on a servomotor; the easiest method to control it would therefore to command its position. However, we do aim to provide repeatable and controlled forces to users, in a precise and accurate way. In this technical evaluation, we therefore study different servoing methods - to optimise Haptixel's displacements, and provide users with accurate forces with a low latency to destination. For all the following, the same procedure was used: we ran cycles by controlling either the servomotor position or speed and measured the applied force; or ran cycles by controlling the applied force and measured its error, position and latency.

1) Force drift with Position servoing: We first attempted to find a correlation between the servomotor's stroke and the applied force over the finger pad. We ran 50 cycles of the servomotor going to $30, 40, 50, 60, 70°$ and back on a participant's finger wearing Haptixel with the TPU (flexible printing) support, and recorded the force and measured the drift in force sensing. This drift in force was consequent (e.g. average force for $50°$ = 0.47 N with a standard deviation of 0.20 N, i.e. $\approx$ half of its value) and could not be predicted, as per Figure 4. As mentioned previously, because of the finger pad deformation and sensor hysteresis, we therefore need to servo our device in force to provide consistent and repeatable force feedback to the users.

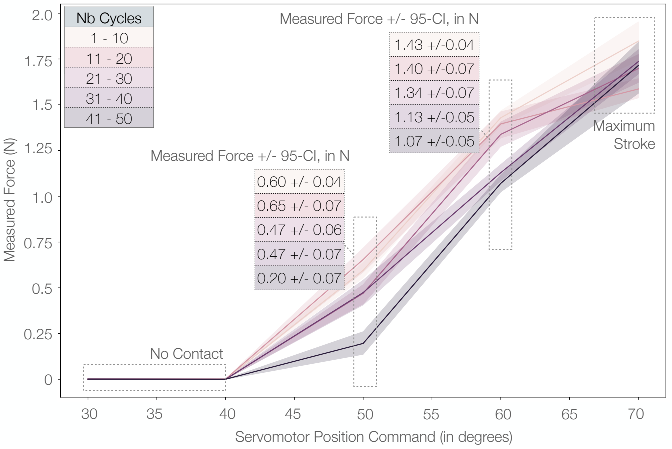


Fig. 4. Force as a function of Servomotor Position and Number of Cycles. Call-outs show force values per range for a position of 50° and 60°. Dispersion of data show 95-CI.

2) Force servoing with Position and Speed control: We then servoed Haptixel in force, by controlling it either in speed or position (see schematics in Figure 5). The control in position consisted in the following:

$$Haptixel\ _{x,y} = Haptixel\ _{x,y} + K_m \cdot \epsilon(Force) \qquad (5)$$

with K_m, a gain empirically chosen to minimise error and limit oscillations.

The control in speed was as described in the Implementation section (see Section III-B).

We ran 20 cycles of Haptixel getting to force levels of $\{1.0N, 1.5N, 2.0N, 2.5N\}$ - then being stable for at least a second, and going back to 0N; using the two control methods (position or speed). Results in accuracy and latency for each force command are displayed in Table II.

Accuracy. Results show that for both methods, the accuracy is around 0.07 N (95-CI = 0.04N).

Latency. The latency for both methods is quite different. When the position method was used, the latency was way higher (1.74s for 1.0N, 95-CI = 0.51s; 3.88s for 2.5N, 95-CI

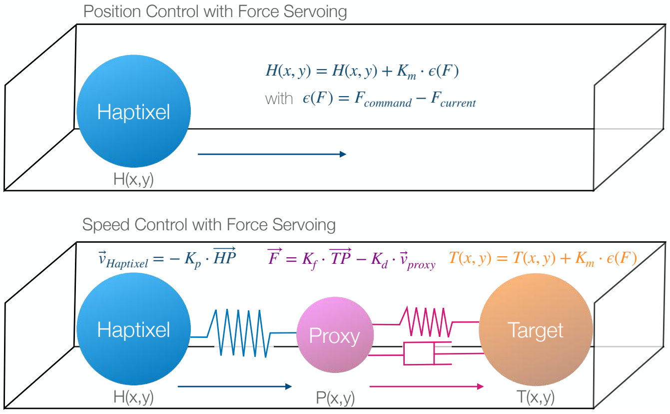


Fig. 5. Schematic of both Force servoing control schemes: Position control or Speed control with proxy.

Latency +/- 95-CI (in s)		
Force Cmd	Speed Control	Position Control
1.0 N	1.04 +/- 0.31	1.74 +/- 0.51
1.5 N	1.44 +/- 0.31	3.85 +/- 0.39
2.0 N	1.76 +/- 0.15	2.72 +/- 0.34
2.5 N	1.50 +/- 0.50	3.88 +/- 0.51
Total	1.44 +/- 0.32	3.04 +/- 0.17

Accuracy +/- 95-CI (in N)		
Force Cmd	Speed Control	Position Control
1.0 N	0.04 +/- 0.05	0.08 +/- 0.04
1.5 N	0.05 +/- 0.05	0.07 +/- 0.04
2.0 N	0.07 +/- 0.04	0.04 +/- 0.05
2.5 N	0.07 +/- 0.04	0.08 +/- 0.03
Total	0.07 +/- 0.04	0.07 +/- 0.04

TABLE II
LATENCY AND ACCURACY MEASURED FOR SPEED AND POSITION CONTROL AS A FUNCTION OF THE FORCE COMMAND; AFTER 20 CYCLES.

= 0.17s) compared to the speed method (1.04s for 1.0s, 95-CI = 0.31s; 1.50s for 2.5N, 95-CI = 0.50s). When the speed controller was used with the proxy, this latter was moving faster towards the targeted position, and therefore was leading the servomotor faster; making the latency independent from the targeted force (1.4s in average, 95-CI = 0.3s). Depending on the use-cases it is used in, Haptixel 's latency when coupled with virtual/digital environments can obviously be reduced using different intention models, for instance predicting the next contact timestamp (such as in [7]).

C. Discussion and Conclusions

These technical evaluations revealed multiple pieces of information regarding Haptixel's capabilities. First, using JND information, we believe we can provide at least three or four levels of forces without having to convey too much force to the fingertip (above 2.5 N). Discrete values (for instance up to 2.5N) could for instance be discriminated properly without overlapping with each other. Moreover, even if users cannot discriminate forces as absolute values, we believe relative forces using a continuous rendering could also be transmitted and used to translate information from a digital environment. Also, Haptixel's encountered-type property conveys an additional contact type: *no contact*.

Second, we show with our control evaluations that our force-servoing method is accurate and precise. The latency (below 1.5s) was calculated from *no contact* to the requested force (up to 2.5N). This latency is of course less important to go from 1.5N to 2N, and Haptixel can provide consistent continuous forces (to go from the one to the other). Haptixel can also be used with intention prediction [3] and contact time prediction [7] models to reduce latency to destination.

From these evaluations, we defined multiple force levels and contact types; we propose to mix and match them into a novel design space to define interaction techniques for pressure-based fingertip haptics, illustrated by Haptixel.

V. HAPTIXEL: DESIGN SPACE

We present Haptixel's design space through its inherent capabilities and the interaction techniques it can leverage; through its visual support, the properties it instantiates (both in-hand and off-hand, e.g. when hovering over visual material), and how these properties can be interpreted (Figure 6). This design space is currently proper to Haptixel, but could be adequate for any future encountered-type pressure and force-based wearable haptic device, servoed in force.

A. Visual Support

Inspired from [33], Haptixel was designed with "mixed feelings" to allow physical feedback in VR, AR, as much as with 2D displays or without any visual support. Haptixel provides force and vibration at different levels, that can be perceived and discriminated even without visual support. It can for instance be used with visually-impaired users to enable perceptions of object contact, object properties, physical depth etc. For displays, it can be used to add a tangible dimension to visual content. In AR and VR, it can either contribute to the same novel tangible dimension (as an augmented bubble plot), to represent 3D objects properties.

B. Force Levels

The fingertip pulps are the most sensitive parts of our body and the most adequate to interact or simply touch any object or surface. It is therefore important to leave this body part unencumbered when no contact is intended (both with and without digital environments). We therefore designed Haptixel as an encountered-type haptic device, as an "on-demand" wearable [2], [3]; it has the ability to let the user fingertip's unencumbered from a continuous force-feedback; **without force** nor physical contact. When touching the fingertip, Haptixel can provide a simple **contact without force**: it senses the fingertip proximity and can adjust according to it to clutch itself [10] and provide the user with a light touch. Finally, Haptixel also provides **low and high forces**, either caressing, touching or pushing on the user's fingertip.

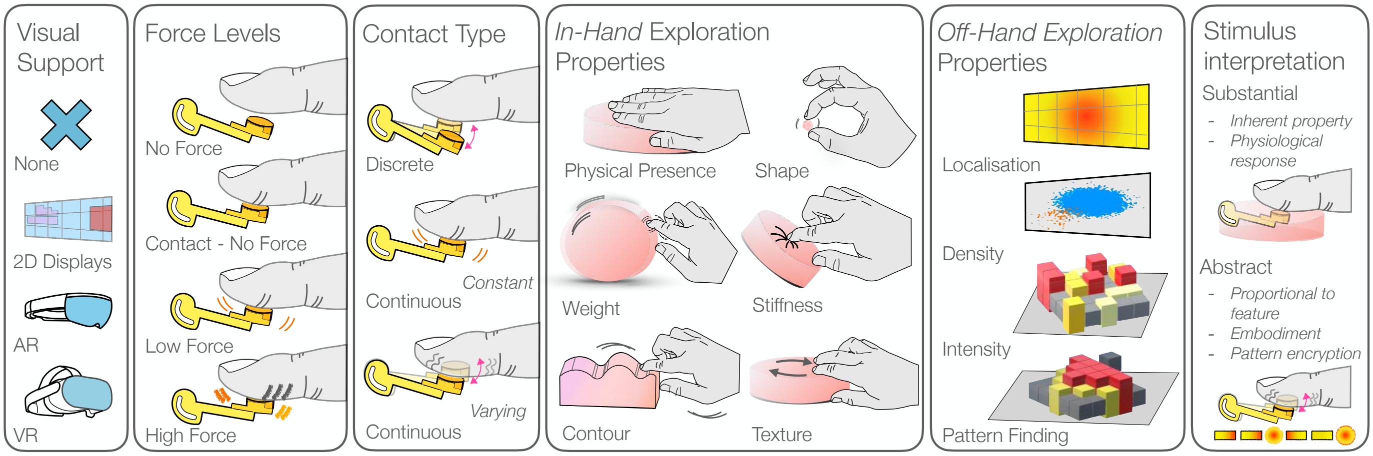


Fig. 6. Haptixel's design space, through 6 dimensions: *Visual Support*, *Force Levels*, *Contact Type*, *In-Hand Exploration Properties*, *Off-Hand Exploration Properties*, and *Stimulus Interpretation*.

C. *Contact Type*

Users' perception will depend on the contact type Haptixel provides. As an encountered-type device, and for the "physical presence" perception, it relies on a **discrete** contact type, like a stroke (on/off). On the opposite, it can also provide **continuous** contact: either a constant force, or a varying one. A **constant force** provides an absolute or a stationary information. As an example, morse code would therefore be a combination of discrete and continuous constant contact types (respectively dots and dashes). Continuous **varying force** rendering would be ascending or descending, indicating more relative information (e.g. stronger, weaker). It can be used to indicate varying levels or intensities in a comparison task.

D. *In-Hand Exploration Properties*

First, thanks to its differentiation between no contact/contact and as per [9], Haptixel provides the perception of **physical presence** [46] in both XR and in real environments. Though, thanks to its design, it can also provide a wide range of *in-hand* exploration properties. We define these *in-hand* exploration properties as properties that can be perceived through our hand in a direct manipulation [47] or exploration [48], e.g. inherent virtual objects or digital objects properties. We exploit Lederman and Klatsky's exploratory procedures and their corresponding object properties [49] to define them.

Haptixel does not impair the virtual hand tracking (see Section III) and therefore can be used in a direct manipulation of a virtual object, to either perform a *precision grasp* [50], [51], e.g. between the thumb and the index finger. Haptixel's force levels can be exploited for this contact rendering: the more users press on the virtual object boundary, the more force they will receive - as a resistance force. The more interpenetration between the virtual object and the real fingers' position, the more force (e.g. a spring-damper model, see Section III); as when pressing on a rigid object in the real environment. This relies on the "continuous varying force" described above, and can provide information on the objects' **global shape**, enclosed within users fingers, and submitted to contact forces. This model can also be used to perceive **weight** properties: the more resistance when pushing or raising an object, the heavier it is perceived. This does not prevent the virtual/augmented objects to be deformable with various **stiffnesses**: the object can deform to its fullest according to its given stiffness, which Haptixel can simulate accurately, and then be moved accordingly with its given weight. Indeed, stiffness and deformation are linked through force, which Haptixel provides. This variation of force can also help to discriminate an object or a surface **contour**: the user can follow it and feel bumps and holes. These can be interpreted as indicators to raise or lower the fingertip, and therefore better understand this object/surface boundary and *local shape*. We believe that Haptixel can be coupled with visual illusions such as [42], [43], [52] when used in VR; to extend its range of perceived stiffnesses, shapes or weights even further. Finally, with a combination of vibration and force-feedback, Haptixel can provide **texture** rendering [19], [20] when exploring the surface of an object.

E. *Off-Hand Exploration Properties*

As opposed to the previous *In-Hand* exploration properties, we define here *off-hand* properties as features that can be transmitted to its user from a hovering distance. They do not require a thorough contour following nor a direct contact; and represent more abstract properties than inherent haptic features from an object. Inspired from data physicalization, consisting in "physical artefact whose geometry encode data" [34], Haptixel can encode information for the user to perceive and interpret. While vibrations have been used to provide notifications [9] or to attempt to represent "data quantity" [53], we believe that using Haptixel to leverage the discrimination of different force levels and the perception of continuous varying forces could benefit these *off-hand* exploration properties. Apart from its vibration capabilities, Haptixel's force levels can indeed be used to encode **localisation** information, with a conveyed force proportional to the distance to a target. Using relative forces levels, its stimulus can also be translated into a varying **density** property [39]. These can also be perceived as varying **intensities**, which can also be perceived through constant forces; conveying absolute information. Combining localisation, densities and intensities, Haptixel can also transmit **patterns**, for instance haptic alphabets [54] (e.g. morse code, blind-deaf haptic language). As per Figure 6 - *Off-Hand Exploration Properties*, the visual supports of intensities, densities, pattern findings, can be expressed as height, color, spread; but these representations are not exhaustive. They can also be perceived without visual support, as per the evoked haptic alphabets.

F. Stimulus Interpretation

As it can be understood from the two different types of Exploration properties, the stimuli Haptixel provides can be interpreted in different ways: its contact type and force level would also impact the understanding of this stimuli. We define two categories for this interpretation: **Substantial**, being a straight-forward stimulus the user would instantly perceive; or **Abstract**, as a stimulus that requires a translation in order to be interpreted properly.

In the Substantial interpretation, we find object's **inherent properties**: when a user enters in contact with an object, they understand the stimulus as being straight-forward. This is valid for most *in-hand* exploration properties. Another example is Intensity, from the *off-hand* exploration property: depending on the visual support, the user would connect a relatively ascending force to a peak when exploring a line graph. The stimulus matches the visual expectation, and is inherently and substantially perceived as it should. Similarly, we also find **physiological responses**. It is shown that the speed or intensity in which we are entered in contact with alters our emotions, such as anger, arousal or stress [55] (e.g. a strong and long stroke as opposed to a light caress touch). This response is inherent in the user's response, and the stimuli would be understood and interpreted with no external or additional information about it.

On the contrary, Abstract stimulus interpretation does require a translation; and the user would have to have the keys to understand it beforehand. For instance, while a localisation task can be seen as substantial, it can still be abstract: a stronger signal could indicate a distance to a target as much as a distance to an obstacle. In both cases, the perceived stimulus is **proportional to the intended feature** (here, a distance). This is also valid for density property; or the previously evoked intensity property if not matched with the adequate visual. This abstract stimulus representation is expressed in data physicalization through **embodiment** - "providing tangible form to something abstract" [4]. Different kinds of exploration properties can be embodied through the force levels and contact types Haptixel proposes; and this embodiment can be relying on color, distance or even non-quantifiable features. Finally, and as per Figure 6 - Stimulus Interpretation schematic, this abstract stimulus interpretation can also be relying on a **pattern encryption**: morse code, blind-deaf language etc. The user would need a translation to understand it. Haptixel can provide numerous combinations of force levels, contact types and vibrations; which the user would have to translate and be initiated with beforehand.

Many exploration properties can be considered as abstract *or* substantial (e.g. intensity, localisation): this stimulus interpretation is highly related to Haptixel's used visual support.

VI. USER EXPERIENCE

We conducted a user experience to demonstrate Haptixel's capabilities for multiple levels of force perception and discrimination in a data exploration task. We chose to evaluate Haptixel using the *Off-Hand* exploration properties from our Design Space (Section V); as an evaluation of in-hand exploration properties would have been too straight-forward. As Haptixel is servoed in force, we do know the forces provided to users - which for instance would obviously alter their stiffness or force perception.

A. Experiment Design

We designed a VR pixel-art like application where participants manually explored physical patterns which they could not visually see - as per Haptixel's design space. Participants had to replicate them as heat maps on a blank canvas with colors matching the force levels (intensities) they perceived (see Figure 7).

1) Participants: We recruited 16 participants (44 % women, 56% men), aged from 23 to 38 (average = 27, std = 4.0). Three participants (19%) were novice in VR, 6 (38%) had already experienced VR (between 2 and 5 times), 5 (31%) were intermediate (between 5 and 10 times) and 2 (12%) were experts. Ten of them (62%) had already tried haptics experiences (ultrasound, pseudo-haptics), but none of them had already experienced wearable haptics; and three of them (19%) were never involved in haptic experiences. Thirteen of them (81%) declared themselves as right-handed, while the rest were left-handed.

2) Procedure: Participants entered the room and were asked to wear Haptixel on their dominant index and middle finger. They were explained the aim of the study, and then were asked to wear the MetaQuest 2 headset. Five different color levels were represented in a continuous map, representing the Force Levels from our design space (Section V): grey (no contact), white (contact but almost no force, = 0.1N), yellow (low force, = 1.3N), orange (medium force, = 1.9N) and red (high force, = 2.5N). Each color is associated to the cube's height as well (the more force, the redder and the higher). Each pixel (e.g. cube) originally measured $5 \times 5 \times 5$ cm^3 and were 2 mm away from each other, to ensure a continuous perception of force when hovering on top of them. We proposed four PATTERNS (cross, triangle, circles, and a random heat map pattern). We chose the random pattern to remove the a priori bias participants might have from drawing known shapes and trying to complete it in a "consistent" way. We controlled the number of force sub-levels to discriminate - cross: 1, triangle: 2 (see Figure 6 - *Pattern Finding*), random: 3 (see Figure 6 - *Intensity*), circles: 4 (see Figure 7 - After Drawing); and participants all performed the four patterns in the same order, to get an ascending difficulty. The discrimination level was indeed increasing, from 2.0N difference at Level 0 to 0.6N at Level 3 (see Table III); The average duration was 45 minutes (std = 10 minutes).

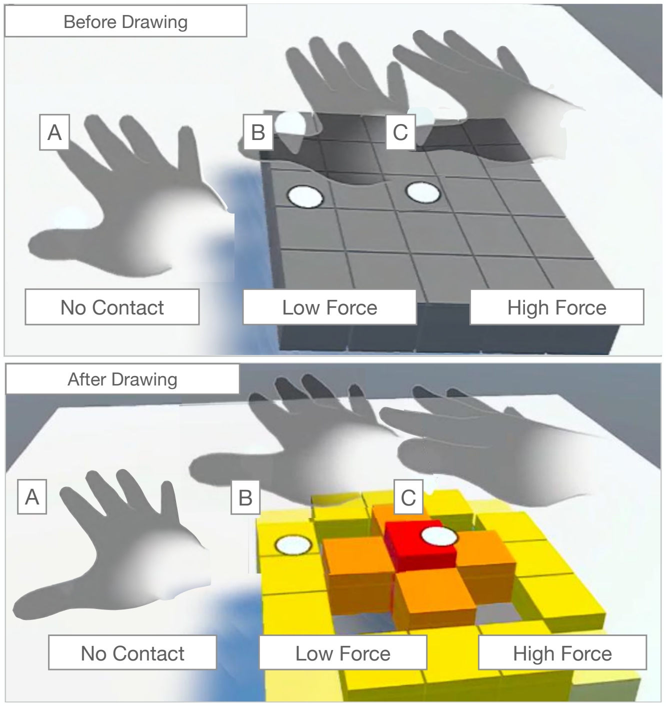
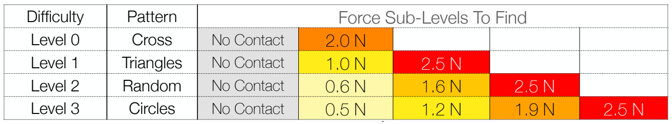


Fig. 7. User experience example: (Before Drawing) The user hovers on top of a blank canvas, and perceives (A) nothing; (B) low force; (C) high force. The user then assigns colors according to their perception. (After Drawing): (A) Still no contact; (B) Yellow color for low force; (C) Red for high force.



Difficulty	Pattern	Force Sub-Levels To Find				
Level 0	Cross	No Contact	2.0 N			
Level 1	Triangles	No Contact	1.0 N	2.5 N		
Level 2	Random	No Contact	0.6 N	1.6 N	2.5 N	
Level 3	Circles	No Contact	0.5 N	1.2 N	1.9 N	2.5 N

TABLE III
LEVELS (DIFFICULTY), PATTERN AND FORCE SUB-LEVELS TO FIND.

3) Stimuli: The virtual scene was designed on Unity3D. The scenario was the following (see Figure 7):

Jess wears Haptixel and the MetaQuest 2, and sees a first cube: it is the Calibration cube. Whenever she hover on top of it, a cursor coming out of her hand selects it. She can change its color and height using +/− on a virtual keyboard using her non-dominant hand, and she simultaneously perceives its corresponding force on her dominant fingertip; as if it mapped a heat map. Once she is familiar with the association color/force, she then presses "Continue" and sees three grey cubes. She feels that each of this cube has an inner force. She then associates each cube's color to the force she perceives, using a virtual keyboard. Once she is confident, she presses on "Continue". She then can feel what she has drawn: when hovering over the cubes, she perceives the force ***she*** *previously associated. If she is satisfied, she confirms and presses "Continue"; if not she reiterates until satisfied. She then sees a 5×5 grey pixel art canvas: the game is starting; using the same process. She explores, feels different force levels, draws, verifies. When she is done exploring and painting her four pixel-art canvases, the game is over.*

4) Design: All participants drew all four patterns, and had a 5-minute break between patterns 2 and 3, to get some rest and free their fingertip from being stimulated. In summary, the experimental design is: 16 PARTICIPANTS × 4 PATTERNS × 5x5 PIXELS = 1600 force discrimination TRIALS.

5) Measures: We measure the users' assigned forces (e.g. *not* the cube inherent ones), and their respective color coding.

B. Results

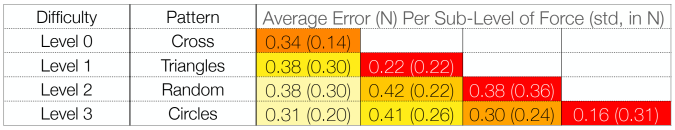
We define here the Absolute results as being the Absolute average force assigned by participants and its associated absolute error (assigned force vs. expected force); and Relative results as the sub-levels discrimination accuracy, the force difference between levels, and the spread of data for a given sub-level (e.g. an absolute offset can occur within the JND, as it should be felt as "non-noticeable"; though if the whole level has the same offset and thus a low spread, the discrimination between forces can still be considered as adequate). We removed 14 values (0.88% of data) as they were considered as outliers (over 3 standard deviations in the pixel value analysis) and performed our analysis over 1586 pixels.

1) Contact vs. No Contact: Haptixel relies on an on-demand mechanism to *either* leave the fingertip unencumbered and free of any contact *or* to provide contact and force over it. In total, 98.9% of the cubes (1568/1586) were correctly assigned (grey/no contact vs colors/contact). Only one cube was assigned a low value (0.04 N) instead of 0 N (white / grey); and 17 (colored) cubes were not assigned (grey).

2) Absolute Results:

a) Global Results: We measured the absolute forces that were assigned per PATTERN, per pixel and per Sub-level of force (see Table III for sub-level references). In Figure 8, each PATTERN is represented as "Pattern To Find" (left) with its respective Average participant drawing counterpart (right, showing the average assigned force and standard deviation). The colors in the heatmap is associated to the continuous color bar indicated on the top of the Figure. We can therefore notice that each PATTERN was correctly drawn; and that each sub-level of force was indeed correctly represented per PATTERN, even though some low offset can still be perceived (e.g. in Random Pattern, Level 2). This will be discussed furthermore in the Relative results section.
The global average error overall ($\epsilon = |pixel_{tofind} - pixel_{user}|$) is **0.19 N**; and the average error in the discrimination tasks (e.g. removing all the grey/0 N cubes) is **0.34 N**.

b) Absolute Error per Sub-Level of Force: The absolute error per force sub-level is shown in Figure IV. In the Triangle and Circle PATTERNS, the error was lower for higher forces (≈ 0.2 N for a 2.5 N expected force) than for the other ones (≈ 0.35 N). These errors levels do fall into the previously demonstrated JND - and therefore demonstrate that absolute forces could be discriminated adequately.



Difficulty	Pattern	Average Error (N) Per Sub-Level of Force (std, in N)			
Level 0	Cross	0.34 (0.14)			
Level 1	Triangles	0.38 (0.30)	0.22 (0.22)		
Level 2	Random	0.38 (0.30)	0.42 (0.22)	0.38 (0.36)	
Level 3	Circles	0.31 (0.20)	0.41 (0.26)	0.30 (0.24)	0.16 (0.31)

TABLE IV
ABSOLUTE ERROR IN N (STD, IN N) PER FORCE SUB-LEVEL.

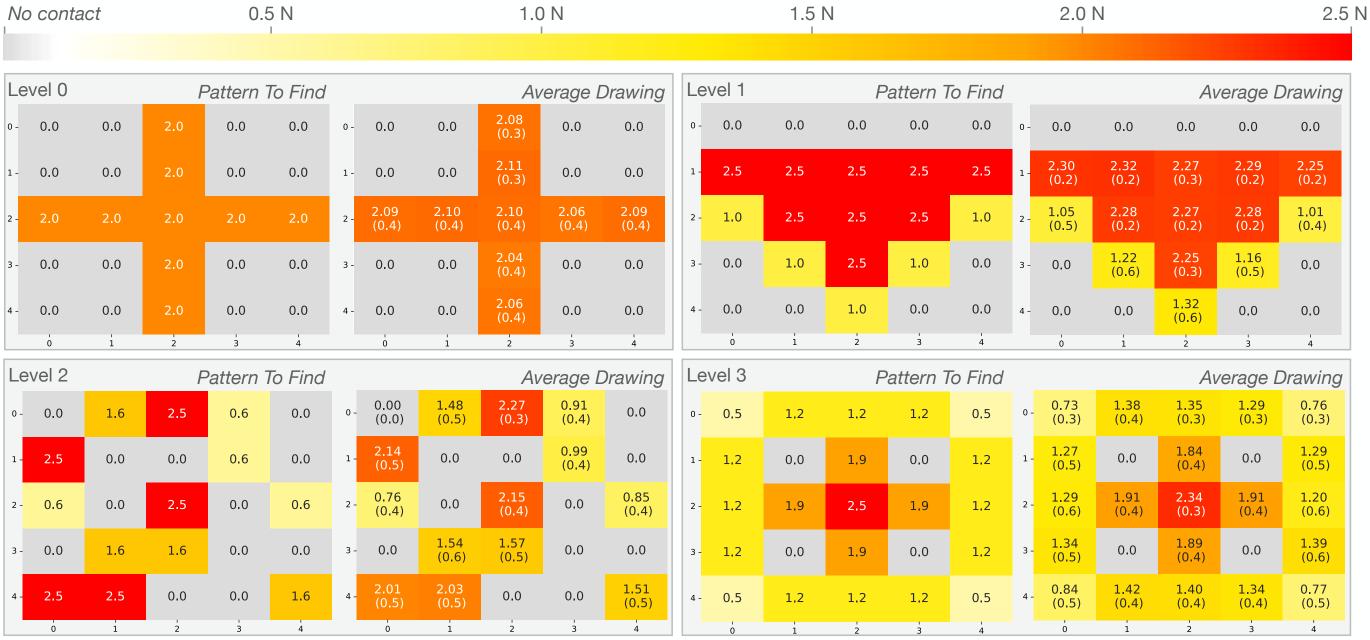


Fig. 8. User Experience Absolute Results: Each Level/Pattern to Find is represented with its associated force, and its corresponding Participant average drawing counterpart is indicated. Each pattern was accurately drawn; and each color level was represented in the same range of colors. These results indicate that Haptixel can therefore be used to discriminate at least 4 levels of force (+ no contact level).

3) Relative Results: As we might see in Figure 8 - Level 1 (Triangle Pattern) or Level 2 (Random Pattern), the average colors users drew are not exactly matching the expected red pixels. Though, the difference between the different sub-levels can still be perceived. Indeed, even though participants might have offsets in their assigned forces, they might still perceive the relative differences of forces (e.g. *stronger, lower*) and/or the pixels that belong to the same force sub-level. Note that no indication that pixels were assigned per sub-level nor the number of sub-level was indicated to the participants. In this subsection, we therefore analyse the relative results, with the relative force discrimination and user data spread.

a) Relative Difference per Level: We had designed the Pattern difficulty according to the force difference between sub-levels. In the Triangle pattern, a difference of 1.5 N was expected between the two sub-levels (1.0 and 2.5N): in average, we report a 1.13N average difference among all users drawing. In the Random pattern, the difference between each sub-level was around 1.0N; we report a 0.59 and 0.65N difference between the sub-levels. In the Circle pattern, the difference between all the sub-levels was around 0.7N; we report relative differences of 0.45N for the $[2.5, 1.9N]$ sub-level, and 0.57N for the $[1.9, 1.2N]$ and $[1.2, 0.5N]$ sub-levels.

b) Spread of Data: As per Figure 8 - Level 1 (Triangle Pattern) - the expected force sub-level is not reached; though the whole set of red-ish pixels share the same color. To quantify it, we here calculated the 95-confidence interval per sub-level **per user** to represent the spread of data within a force sub-level and to indicate whether participants did recognize which pixel provided the same levels of forces; and averaged it out for each Pattern's force sub-level. Results are displayed in Table V: the more the expected force, the lower the spread of data (from $\leq 0.3N$ to $\leq 0.1N$). These results therefore indicate participants were confident pixels were associated among one sub-level.

Difficulty	Pattern	Average User 95-CI (N) Per Sub-Level of Force			
Level 0	Cross	0.06			
Level 1	Triangles	0.33	0.05		
Level 2	Random	0.20	0.28	0.20	
Level 3	Circles	0.28	0.14	0.10	0.0

TABLE V
AVERAGE USER 95 CONFIDENCE INTERVAL PER PATTERN'S FORCE SUB-LEVEL. THESE RESULTS FOR INSTANCE INDICATE THAT IN AVERAGE, ALL PARTICIPANTS CONSIDERED ALL OF THE TRIANGLE PATTERN RED PIXELS TO BE EQUAL, WITH 95% OF THE DATA INCLUDED IN A $+/-0.05N$ RANGE.

c) Cube Discrimination in Level 3 (Circle PATTERN*):* We analysed Haptixel ability to provide different levels of force by conducting a one-way repeated measures ANOVA. We first verified ANOVA's assumptions (normality, equal variances) and none were violated. There was a significant effect on the sub-levels (F(3,27) = 96.3, p $<$ 0.001, η^2 = 0.9). Posthocs pairwise T-tests with Bonferroni-corrected p-values were then calculated, and significant effects were found between all the different sub-levels, with p-values $<$ 0.001) (see Figure 9).

4) User Observations and Qualitative Feedback: Most of the users revealed that it was easier to draw the patterns by relying on relative force perception. The calibration was helping defining a first reference color, but as the distance between this latter and the canvas was over 7cm, they had to focus and play on their own pressure/force memory to get an adequate color matching. They were then using their relative perception of forces from one cube to another, and then validated using the calibration cube once a first drawing was done. The "validation" phase, where they could perceive

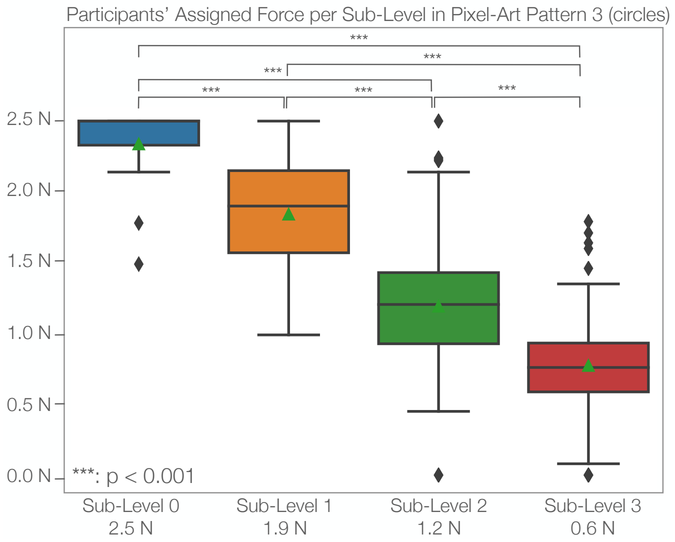


Fig. 9. Boxplot of participants' absolute assigned forces per sub-level in Level 3; significance reveals that sub-levels were indeed discriminated.

the drawing they had drawn, usually helped to detect a global offset of the whole pattern. One participant mentioned it was fun to focus on pressure memory, as it is a quite unusual task - compared to shape memory for instance. All participants mentioned the experiment was fun and original, and were surprised by the (large) amount of force Haptixel provided.

C. Discussion

Our user experience contributed in demonstrating Haptixel 's ability to provide different levels of forces; which users can discriminate. There was a significant effect between all the participants' assigned forces per sub-level, therefore indicating that at least four sub-levels can be discriminated as different from each other. Relative force levels (*stronger, lower*) were also felt from one pixel to another, and pixels belonging to the same force levels were recognized and acknowledged as similar - with a really low spread of data. All these assigned forces were within the same JND threshold, which confirms our previous findings in terms of force noticeable difference. This finding do illustrate that Haptixel can be used for *Off-Hand* Exploration properties; as localisation, density and patterns can be perceived using relative forces. More importantly, the participants' absolute assigned forces were close to the ground truth (0.34 N global error), with errors values under the JND calculated in Section IV. This illustrates how Haptixel can be used to interpret intensities and to provide information proportional to its rendered force.

With this experiment, we also demonstrate that forces Haptixel provides can be discriminated without any visual help or bias. The initial canvas being entirely grey, participants therefore identified absolute and relative forces with no visual support, or with a wrong color (e.g. when the colors are being changed). Our results indicate that Haptixel can indeed be used outside of VR, to provide force, pressure or depth content as per our Design Space (see Section V); with for instance localization, density or intensity information.

VII. ILLUSTRATIVE USE-CASES

As mentioned before, Haptixel can be used for a whole set of use-cases combining multiple dimensions from its design space. We propose here a set of use-cases (see Figure 10), that may rely on various visual supports.

A. Geographic Data Physicalization, Urban Planning

As illustrated in Figure 10 - A, Haptixel can be used for surveying a geographic map or any maps of the sort. With a real map, a 2D screen, or even a wall-sized display [56], Haptixel can convey topography information, can help track and follow rivers, check population density etc. These dimensions can be available visually and matching Haptixel stimulus, or intrinsically transmitted through Haptixel, and providing an additional dimension.

In more immersive environments such as AR and VR, where the map would be in 3D, Haptixel can provide direct in-hand exploration properties on the 3D data under a tangible form, such as in [57]. This can also be used in Urban planning use-cases, where users could also modify the city topology, its architecture, or perceive densities of traffic.

While participants could explore and/or manipulate data in hand, this can also be performed in collaboration with others; not necessarily sharing the same visual support. As per our user experience, one could draw and the other could feel what was drawn; or one could draw and convey information to a collaborator, perceiving it physically and instantaneously.

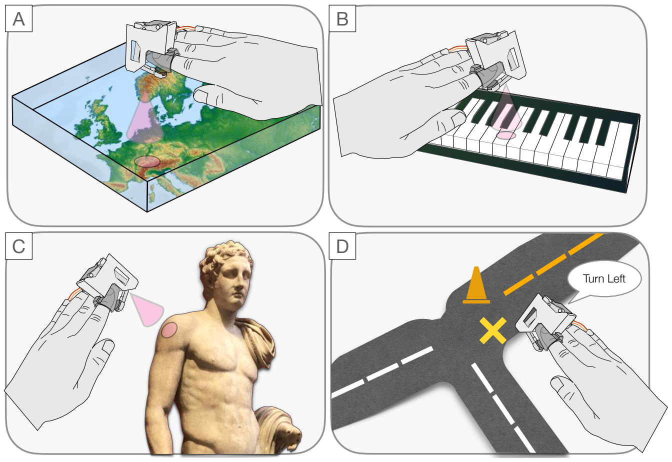


Fig. 10. Example Use-Cases: (A) Geographic Data Physicalization; (B) Piano Mentoring; (C) Museum Exploration - Volumetric Data Physicalization; (D) Navigation example.

B. Keyboard Interaction

Haptixel can also be used to perceive interaction with a virtual or augmented keyboard in AR/VR. It could also be extended to more fun types of keyboards, such as a virtual piano (see Figure 10 - B) [58]. When hovering over the piano, Haptixel can provide practice, and provide a contact with the user when the expected piano key is required to be pressed. It could also provide a key stiffness perception, to inform the user on the expected force that should be applied on the key - still in the mentoring phase. In a practical phase, the user could play the piano at a hovering distance (or not) in these immersive environments.

The use of keys can also refer to the haptic alphabets we mentioned previously. We can create languages using stiffnesses, contact speeds, continuous constant/varying contact types etc. A user could use Haptixel to perceive and decrypt a code and write using it: the user can interact with a key, perceiving the force level (e.g. function of finger/object interpenetration) and contact type (continuous, discrete etc).

C. Volumetric Content Physicalization

Haptixel can provide *in-hand* exploration properties that were inspired from [49]; though these properties can also be felt from a distance, when the direct manipulation is not allowed - for instance in a museum (see Figure 10 - C). Multiple scenarios are available: depth from a given location can be translated into pressure types; or a statue/painting can be scanned and replicated in augmented/virtual environments, scaled down, and explored *in-hand*. Haptixel can replicate and physicalize volumetric content, so users can feel contours, materials, and thoroughly explore without altering the physical conformity of a statue or a painting.

Haptixel can also be used to provide haptic properties to an augmented/virtual environment; for instance with realtor visits, where users can choose their furniture in XR; or in the automotive industry, to choose the interior of a car passenger compartment in XR.

D. Navigation

Haptixel can be used for navigation guidance, coupled with a GPS to provide a height/depth information; as a more substantial information, or to provide directions with an encrypted pattern (see Figure 10 - D).

Its signal intensity can also communicate a distance to a target, as much as a distance to an obstacle (in an obstacle avoidance task).

This navigation can also be performed in other types environments: Haptixel could transmit constraints information in a teleoperative task for instance, to inform of the remote surroundings (walls in a remote building, tissues to avoid in a remote or virtual surgery). It could also potentially be coupled with a device such as the *EyeRing* [59], to physicalize and convey its retrieved information.

It can be used with/without visual support, for visually impaired as much as for providing an additional dimension for users in the real life, in AR or in VR.

E. Graph Data Physicalization

As mentioned throughout the paper, Haptixel can be used for data physicalization (see Figure 1 - Bottom), whether the data is in bars, lines, scatter, heatmaps etc. It can be used for every visual support, and in collaborative tasks. One can imagine a participant pressing a button where the intensity of the dimension would be proportional to its hand/button interpenetration; the other participant could then hover on top of the data and perceive that prior dimension.

VIII. PERSPECTIVES & FUTURE WORK

We demonstrated Haptixel's capabilities both technically and with participants, perceiving *pixels* force difference and replicating it. In the future work, we believe Haptixel could be extended to more fingers, miniaturized, or integrated with other technologies such as controllers or exoskeletons. Its design space relies on pressure and force-based haptics; with contact types and force levels. Future work includes an extension of this design space by coupling Haptixel's vibratory capabilities - which are out of the scope of this current paper.

A. More Fingers, Less Cumbersome

Haptixel is currently focused on the index finger (for left-handed as much as right-handed). We believe that using our flexible printing, Haptixel could fit on other fingers, and the size of the finger support can for instance be adjusted for the pinky finger. Future work include the integration of the whole hand. We would like to provide a full-hand system that could literally fit like a glove; without restraining the fingers relative position to each to other. The constraints in this design would still include the ability to not disrupt hand tracking from external systems such as the Meta Quest. Some miniaturization work should also be performed to make Haptixel even lighter and less cumbersome; especially for the real-life scenarios. We believe that a more deployable version of Haptixel should fit in one's pocket and feel as transparent as possible.

B. External Integration

We also consider integrating Haptixel in exoskeletons or controllers. In [7] for instance, it is shown how a palmar encountered-type contact improved manipulation with exoskeletons in VR. As Haptixel relies on a similar concept, we believe it would benefit exoskeletons manipulation by adding richer haptic stimulation to the users' fingertips. We believe Haptixel's crank-rod mechanism can even be integrated directly within the exoskeleton mechanism. This would allow to remove the servomotor and to have an even lighter version of Haptixel , to integrate as a custom unit in exoskeletons such as the DIY low-cost LucidGlove[2].

C. Comparison/Coupling with Vibrations Capabilities

While this paper focused on conveying information through pressure-based fingertip haptics, we do acknowledge how vibrations are being used with other wearables haptics. Wearable haptic devices involving vibrations on the fingertip usually rely on a constant contact with the finger such as [60]; or can encounter it [9]. While the vibration intensity can vary and take different forms (transient signal [61], continuous stationary signal, continuous varying signal [62]), no device has ever coupled vibration combinations with pressure and force-based ones in a self-contained design such as Haptixel (already containing a vibration motor). Future work hence includes (a) a comparison of these stimuli and their associated user perception; (b) the investigation of a novel interaction design space combining vibration and pressure-based stimuli combinations.

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[2] https://github.com/LucidVR/lucidgloves

IX. CONCLUSION

In this paper, we proposed Haptixel, a novel lightweight DIY encountered-type wearable unit, which concept is to encounter the users fingertip pulp to provide pressure and force-based fingertip haptics and physicalize digital/virtual content. Haptixel was evaluated technically, showing a great accuracy (under 0.04N) and a low latency (under 1.5s). We demonstrated a significant effect of the printing material for Haptixel's finger support, and its impact on the users' JND. Flexible printing allows for a better finger pad deformation, which Haptixel relies on to provide force-feedback. Haptixel aims to physicalize both in-hand and off-hand exploration properties, and to convey both substantial and abstract information. It benefits from various force levels and contact types, and can be used with or without visual support. Haptixel's design space was then illustrated through a user experience showing a great accuracy for absolute force perception (0.34N) and for on-off contact (99% accuracy), and with use-cases including navigation guidance, urban planning, piano training or geographical data manipulation.

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X. BIOGRAPHY SECTION

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