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WallTokens: Surface Tangibles for Vertical Displays

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Figure 1: (Left) Two users interacting with WallTokens on a wall display. Each WallToken can be manipulated on the surface or attached to it. (Right) Close up of a user attaching a WallToken to the wall.

ABSTRACT
Tangibles can enrich interaction with digital surfaces. Among others, they support eyes-free control or increase awareness of other users’ actions. Tangibles have been studied in combination with horizontal surfaces such as tabletops, but not with vertical screens such as wall displays. The obvious obstacle is gravity: tangibles cannot be placed on such surfaces without falling. We present WallTokens, easy-to-fabricate tangibles to interact with a vertical surface. A WallToken is a passive token whose footprint is recognized on a tactile surface. It is equipped with a push-handle that controls a suction cup. This makes it easy for users to switch between sliding the token or attaching it to the wall. We describe how to build such tokens and how to recognize them on a tactile surface. We report on a study showing the benefits of WallTokens for manipulating virtual objects over multi-touch gestures. This project is a step towards enabling tangible interaction in a wall display context.

CCS CONCEPTS
• Human-centered computing → Haptic devices; Gestural input; Collaborative interaction.

KEYWORDS
Tangible Interaction; Tokens; Wall-sized display; Fabrication

ACM Reference Format:

1 INTRODUCTION
Large, ultra-high resolution displays (wall displays) make it possible for one or several users to interact with large volumes of data. Unlike horizontal screens such as tabletops, vertical displays make it possible for an audience to observe a scene from roughly the same perspective, which is particularly important when that scene has a preferred orientation – e.g., text documents or maps. Users can also explore that scene at different levels of detail through physical navigation (stepping close to see the details, stepping back to gain an overview). However, designing efficient interaction techniques for large vertical displays is particularly challenging. Distant interaction can rely on mid-air gestures [36] or personal devices used as remote controllers [6, 21]. Close interaction can rely on touch gestures (e.g., [30]). The latter have the advantage of leaving users’ hands free of any controller, but they also lack precision and hardly scale to concurrent interactions from multiple users.

Surface tangibles can enrich interaction from close distance with a large surface. As opposed to tangibles that are tracked in the air (with e.g., an external optical system), surface tangibles get tracked by the system when they are in contact with the surface.
They enable precise manipulations [13, 15, 43], support eyes-free control [21, 45], can encourage specific collaboration strategies [2, 12] or increase awareness of others’ actions [8]. Such tangibles have been considered to interact with horizontal surfaces, e.g., [23, 33, 50], or with specific supporting structures [44]. But they cannot easily be used with large vertical surfaces as multiple tangibles become cumbersome when they are not left on the display.

In the non-digital world, people work with tangibles on vertical passive surfaces. Whiteboards with magnets, investigation boards with pins and threads, architect desks with drawing tools are all examples of tangibles on vertical or inclined surfaces. However, when it comes to vertical surfaces that actively emit light such as LCD or LED screens, the use of tangibles raises issues. Simple tools just fall, while pins and magnets damage electronics in screens.

In this article, we introduce WallTokens as a means to prototype tangible interaction for vertical surfaces (Figure 1). A WallToken is a light, passive tangible that is mounted on feet in order to generate a multi-touch pattern (i.e., its footprint) when put in contact with the wall. A push-handle, located at the token’s center, controls an additional foot which is equipped with a spring and terminated by a suction cup. Pushing this handle brings the suction cup in contact with the surface, attaching the token to the wall. Once attached, the token can be manipulated as a rotary knob, or left as is to free the user’s hands for any other action. Users can easily detach a token with a simple lever movement that uses any of the peripheral feet as a pivot. This pulls the suction cup away from the wall, which makes the central foot contract back. Users can thus attach and detach tokens at will, making it easy to switch between different tokens or between barehand gestures and token manipulations.

In this article, we detail the design and fabrication process of WallTokens, which relies on 3D printing and basic supplies (i.e., springs and suction cups) only. We describe how well they get recognized on our wall display, which is equipped with an infrared frame for detecting multi-touch input. In a study, we compare the performance of tangibles and multi-touch gestures for manipulating virtual objects, showing that participants’ experience is better with tangibles than with multi-touch gestures. We finally report on our prototyping experience with a sample of applications that we developed on top of our library for handling token input.

Our main contributions are:
- a solution to enable tangible interaction for vertical displays;
- a low-cost approach to the prototyping of such tangibles;
- a study in which tokens performed better than multitouch gestures for manipulating virtual objects.

2 RELATED WORK

Our contribution is to enable tangible input in the context of vertical displays. We review previous work that discusses the individual benefits of vertical surfaces and tangibles for interaction, before detailing the very few projects that combine tangible input with vertical displays.

2.1 Horizontal vs Vertical Surfaces

A few studies have observed the effect of display orientation on users’ experience. First, Morris et al. [34] have studied the impact of orientation for additional displays in an office environment for single users, and have reported that horizontal displays can cause ergonomic discomfort for some tasks such as reading long documents in comparison with vertical ones. A vertical orientation is thus preferable in some cases, particularly when the information space has a reference orientation.

In a collaborative context, Rogers and Lindley [41] conducted a study where teams of three participants had to solve a trip planning task. They compared three conditions: a desktop+mouse control condition, and two larger (∼1×1 meter) shared display conditions with a single pen controller that users have to exchange. The two shared display conditions differ in the display orientation: horizontal (table) or vertical (wall). Overall, the horizontal condition seemed to better promote collaboration between participants. A possible reason why users may have preferred the horizontal condition is the ease of both exchanging the pen and switching between paper-based and digital activities. In the vertical condition, participants complained about the fact that there was no obvious place to put the pen down. Interestingly, in Potvin et al.’s study [38] where each participant had their own pen and could keep holding it, there was no clear difference between the horizontal and vertical orientations for completing a design task collaboratively. These results suggest that tangible artefacts can be cumbersome when working with a vertical display if users cannot easily put them down somewhere.

2.2 Benefits of Tangibles

The HCI literature has proposed applications that rely on tangibles for collaborative interaction in many domains such as art [23], education [2], design [16] or document editing [51]. There are also empirical results that support tangibles’ advantages in such contexts. For example, in Schneider et al.’s study [42], pairs of apprentices in logistics had to design a warehouse on a tabletop using either multi-touch interaction or tangibles. In such a high-level, problem-solving task, tangibles were preferred over touch gestures because they offered a better support to the exploration of alternatives. Antle et al. also showed that tangibles can be beneficial to the implementation of specific design strategies that enforce or encourage exchanges between users [2, 12]. Finally, Cherek et al. report on a study where participants were playing a game on a tabletop and had to react to others’ actions while playing [8]. When performed with tangibles, actions were better detected than with virtual objects, suggesting that tangibles increase awareness of others’ actions, which is key to collaboration [10, 14].

Tangibles have also been studied at a lower level, demonstrating their efficiency for fine-grained manipulations of virtual objects. In their seminal study, Fitzmaurice and Buxton [13] show that enabling space-multiplexed input with multiple specialized tangibles offers more precision than a time-multiplexed input device such as the mouse. Later, Tuddenham et al. [43] compared the performance of multi-touch and tangible input when interacting with virtual objects displayed on a tabletop. They considered both a simple docking task and a pursuit task that involves four objects as in Fitzmaurice and Buxton’s study. In these studies, participants were faster and more accurate with tangibles than they were with multi-touch manipulations.

The advantages of tangibles have been further supported by other studies. Voelker et al. [45] report on a study where they compared...
physical knobs and virtual knobs (manipulated with one or two fingers). They found that physical knobs outperform virtual ones (in terms of both speed and accuracy), and that one-finger virtual knob performance degrades relatively more when used eyes-free than the other two conditions (whose performance remained mostly unchanged). Hancock et al. [15] propose tangibles with a mounted trackball that provides an additional control dimension. They report on an experimental task that consists of manipulations with multiple degrees of freedom (DOF). Compared to touch gestures, tangibles did not significantly differ for 5-DOF tasks, but were much faster for 3-DOF tasks. Participants also felt more precise when controlling a parameter with tangibles, in particular for the data exploration task that they studied. However, Hancock et al. also mention the occlusion issues that can occur with tangibles. Finally, Tangible Tiles [48] is a system that provides a collection of transparent tokens for manipulating digital images on a tabletop. In a task where pairs of participants had to explore images to find hidden features, manipulations with tangible tiles were still less efficient than manipulations of paper images, but they were more efficient than single-touch manipulations.

### 2.3 Wall Displays and Tangibles

As mentioned in the introduction, locomotion is key to interaction with wall displays. Users interact with the wall both from close-up and from afar [1]. This means that the design of tangibles for wall displays should consider (at least) the following two themes in Hornocker and Buur’s framework of Tangible Interaction [18]: tangible manipulation to act on digital information through manipulation of material objects, and spatial interaction to take into account users’ physical navigation in front of the wall.

Distant actions for interacting with a wall display can be performed with mid-air gestures (e.g., [36]) and with physical objects such as personal devices (e.g., [6, 47]) or custom-made objects that are manipulated in the air [3]. However, when it comes to interaction within arms’ reach, surface tangibles have almost never been considered. Surface tangibles refer to physical controllers that users put or slide on the surface, as opposed to tangibles that are manipulated in the air (as the brain prop in [3]) or on another surface (as the sliders attached to a tablet in [21]). To the extent of our knowledge, the only example of such surface tangibles for a wall display is the Miners project [46] that makes use of tangible-touch interactions for a multi-player game. Such interactions proved very engaging for users. However, the use of tangibles remains underexplored, as each player manipulates a single token that is associated with a specific action. Furthermore, each player must always hold the token in their hand. Our contribution with WallTokens is to enable an interaction style where users can not only manipulate tokens on a vertical surface but also leave them in-place on that surface. This makes it possible for users to pin tokens at locations of interest, to switch between different tangibles or to simply free their hands when needed.

Many possibilities can be considered for fabricating tangibles. In the context of horizontal displays, solutions include optical sensing to track fiducial markers attached to the tangibles (e.g., [23, 48]), capacitive sensing with tangibles that create specific multi-touch patterns when in contact with the surface (e.g., [33, 50]), magnetometers or Hall sensors with magnetic tokens [4, 27, 28], or even more elaborate electronics with, e.g., wireless communication [9]. But, whatever the technology considered, there is no obvious way of making it work on as is with a vertical surface. The main issue to address is that of gravity, which prevents users from dropping tangibles without them falling to the ground.

### 3 WALLTOKENS

WallTokens are tangibles that are low-cost and easy-to-fabricate, making them ideal for prototyping. They consist of basic supplies (spring, suction cup and felt) and 3D printed parts assembled together. They are passive, designed to be interacted with on multi-touch surfaces. Like some previous projects (e.g., [5, 21, 25, 33]), each WallToken is mounted on feet that generate a multi-touch pattern when in contact with a tactile surface. A pattern is specific to a token, making this token recognizable with a pattern matching algorithm.

#### 3.1 Fabrication

A WallToken consists of several modular components that are then assembled together by means of screwing and interlocking. Figure 2-left details these different components.

- The base ④ is the main component. It consists of a plate with three feet underneath (i.e., a single 3D printing job). When in contact with the wall, the three feet will generate the multi-touch pattern (i.e., the token footprint) that is specific to the token. Each foot is 25 mm tall and 12 mm wide. In order to avoid any scratch on the surface, each foot is carved with a placeholder where a piece of felt can be glued (each placeholder is a 4 mm side square of 1 mm depth). The plate is 3 mm thick. Its shape can vary (e.g., square, circle, triangle as illustrated in Figure 2-right). The plate not only gives the token a visually identifiable shape, it also prevents users’ fingers from getting too close to the screen and thus interfering with the token footprint during the recognition process.

- The grip ③ is the knob where users put their fingertips to hold and manipulate the token. It is connected with the base thanks to a snap fit system. The grip is a 20 mm high cylinder of 4.85 mm radius at its base. Its contour is slightly curved to make it comfortable.

- The push-handle ① is the top of the token. It is under the palm of users’ hand when they hold the token. It is 15 mm long from the base to the tip, and the radius of its circular base is 16 mm. Users push this handle with their palm when they want to attach the token to the surface. To detach a token, users pull its grip. This creates a lever effect around one of the token’s feet, making this action easy to perform.

- The central rod ⑤ is a 61.5 mm tall stick that connects the suction cup, which can attach the token to the surface, to the push-handle. By default, the suction cup is not in contact with the surface. The bottom of the central rod is designed as a placeholder where the suction cup can be snapped. The top of the central rod ends with a thread on which the push-handle can be screwed.
• The suction cup \( \textcircled{6} \) is a standard 20 mm diameter one, which generates a suction force of approximately 130 newtons. When the central rod is at its default height, the suction cup does not touch the screen, remaining 15 mm away from it.

• The spring \( \textcircled{2} \) maintains the central rod at its default height when the suction cup is not attached to the wall. It has 10 coils and is made of steel (AISI 304L stainless steel). Its length is 25 mm when free, 7 mm when compressed. Its inner diameter is 0.7 mm, and its outer diameter is 0.9 mm.

WallTokens are low-cost, yet robust. They do not require any electronics, but only passive materials. Apart from the suction cup, the spring and the felt, individual components are fabricated with a 3D printer using PLA or Tough PLA filament.\(^1\) The assembly time for a token is less than a minute once the felt has been glued under the feet. We ran some informal tests to assess how long tokens can stay on the wall with such a design. Our tests revealed that they do not fall off for at least twelve hours when the wall is off, and for at least three hours when it is on (heat has an impact on how well the suction cups stick). WallTokens also proven quite robust against repetitive manipulations. In particular, we used the same unique token for the experiment that we report in section 4. However, in case a component gets broken, the modularity of the fabrication process makes it easy to replace the damaged part only.

Finally, modularity also makes it easy to test different token appearances, thus compensating for the lack of flexibility tangibles usually suffer from when it comes to customizing their appearance (e.g., their shape or color) [42]. For example, interaction designers can test different bases during the design phase of an application. Having designed tokens ourselves, we also found modularity very convenient for deciding on ergonomic details. In particular, we have tested several alternatives for the push-handle and grip components before choosing the ones that were the most comfortable during manipulations. SDF files for fabricating the different components are available as supplemental material. Others can easily use them as is, or edit them to test alternative shapes for the base, grip and push-handle.

\(^1\)We used Ultimaker 3/3X 3D printers.

3.2 Recognition

As mentioned above, we rely only on multi-touch tracking in order to recognize a token based on its footprint using the pattern matching algorithm from [33]. A token set is represented by a collection of templates, with one template per token. Then, when at least three contact points occur simultaneously,\(^2\) they are processed with the pattern matching algorithm in order to identify the closest template. Relying on such a recognition strategy means that all tokens’ footprints should be different from one another within a token set.

When a token is in contact with the wall, any contact point occurring inside the triangle formed by the token feet triggers the detection of the attached state of that token. The token’s state remains set to Attached until a token-up event occurs. Such an event occurs as soon as two token feet are lifted off the surface.

Although WallTokens could be made conductive to work with a capacitive surface, very large tactile surfaces usually rather rely on optical tracking for detecting touch input. We designed WallTokens to interact with such a very large wall display, which is made of tiled ultra-thin bezel screens. It is equipped with a PQlabs infrared touch frame, which is located 4.5 mm in front of the screens. Detailed specifications for such a technology are not available. We thus had to conduct a series of empirical tests to assess 1) the minimal diameter of a foot to be detected as a touch point (12 mm), 2) the minimal height that feet should have to keep the token base and the suction cup when in its default state out of tracking range (25 mm), and 3) the minimal distance between two feet to avoid getting them merged as a single touch point (\(D_{\text{min}}=5\) mm).

The tests mentioned above also revealed occlusion issues related to the infrared technology, which impacted our strategy for designing tokens’ footprints. A foot, which is both aligned with a second foot along the x-axis and with a third foot along the y-axis, is not detected. In order to minimize the chances for such an issue to occur, the three feet of a token always form an isosceles triangle. Figure 3 illustrates feet configurations for the nine tokens in our set. The smallest footprint is a 58 mm side equilateral triangle. It corresponds to the smallest footprint that ensures a minimal distance

\(^2\)Contact points should occur within 200ms, and should be close enough to the recognizer’s best match.
A colored shape stimulus is displayed on the wall at 1.25 m above the floor in front of the user. Participants have to grab the token whose shape and color match that of the stimulus (e.g., the pink triangle token in Figure 4) and put it in contact with the wall at the stimulus’ location. This makes the stimulus disappear, and another stimulus appear 60 cm to the right. Participants have to put the token in contact with the wall at this new location. The stimulus’ texture turns into a checkered pattern after a 1-to-2 s random delay. As soon as the texture changes, participants have to attach the token to the wall as fast as possible. In order to make sure that the token is actually attached to the wall, participants have to release the token to touch a green circle that appears close to the token. They then have to put their hand back on the token to be ready to detach it. The stimulus’ fill texture turns into a checkered one after a 2.5 to 3.5 s random delay, instructing the participant to detach the token from the wall as fast as possible. A final stimulus appears 30 cm to the left. It is filled with a checkered pattern as soon as it appears, indicating to participants that they should place the token in this location and attach it as fast as possible.

### Task

As Figure 4 illustrates, our experimental task consists of several steps in order to challenge the recognizer in different contexts. A colored shape stimulus is displayed on the wall at 1.25 m above the floor in front of the user. Participants have to grab the token whose shape and color match that of the stimulus (e.g., the pink triangle token in Figure 4) and put it in contact with the wall at the stimulus’ location. This makes the stimulus disappear, and another stimulus appear 60 cm to the right. Participants have to put the token in contact with the wall at this new location. The stimulus’ texture turns into a checkered pattern after a 1-to-2 s random delay. As soon as the texture changes, participants have to attach the token to the wall as fast as possible. In order to make sure that the token is actually attached to the wall, participants have to release the token to touch a green circle that appears close to the token. They then have to put their hand back on the token to be ready to detach it. The stimulus’ fill texture turns into a checkered one after a 2.5 to 3.5 s random delay, instructing the participant to detach the token from the wall as fast as possible. A final stimulus appears 30 cm to the left. It is filled with a checkered pattern as soon as it appears, indicating to participants that they should place the token in this location and attach it as fast as possible.

### Design and procedure

**Factor and Design.** The only factor is TokenTarget. It can be one of the nine tokens of our final set (Figure 2-right): RedCircle, RedRectangle, RedTriangle, WhiteCircle, WhiteRectangle, WhiteTriangle, PinkCircle, PinkRectangle, PinkTriangle. During the experiment, each participant has to complete one block per TokenTarget, each block consisting of four replications of the experimental task described above. We use three different presentation orders for the nine blocks, one per participant. This design results in 108 completed tasks in total (3 participants × 9 TokenTarget × 4 replications).

**Measures.** The token recognized by our algorithm is logged at steps 1, 2, and 3, allowing us to compute accuracy of token recognition (RecognitionAccuracy) over 108 × 3 = 324 observations. Regarding state detection, the green circle appears after step 4 only if our algorithm actually detects the Attached state. In case it does not, the current task is canceled (with already recorded measures ignored), the operator counts an error (StateDetectionError) and restarts the task. StateDetectionError is incremented each time such an error occurs. The experiment software additionally logs two time measures: AttachTime, which is the time between the first texture change and the Attached state detection that follows (step 3), and DetachTime, which is the time between the second texture change and the token up event that follows (step 5).

**Procedure.** Participants stand about 45 cm in front of the wall. The nine tokens are available on a table to their left. The session of tasks begins with a series of nine practice tasks, one task per token. Participants are allowed to redo the practice set until they feel comfortable enough. They then perform the 36 measured tasks.

### Results

Table 1 reports the overall recognition accuracy, as well as a break-down per participant (A1, A2, and A3) (means and 95%-CIs).
Overall, seven token recognition errors occur among 324 measures. Two occurred at step 1 (both for participant A2), five at step 7, and none at step 6. There was no systematic pattern regarding the confusion errors. This prevents us from drawing conclusions regarding the design of the tokens, as errors might as well result from the touchframe itself, which delivers noisy input on some rare occasions. Regarding state detection, there was only one error among 216 measures. This error occurred with the smallest token (PinkCircle), which happened for A2 at step 7.

Time measures suggest that attaching and detaching a token can be performed in less than a second and that it can take an expert user as little as 500 ms to attach a token already in contact with the surface (time at 2 includes reaction time, and time at 6 additionally includes a movement), and 650 ms to detach a token (4 includes reaction time). Comparing time for attaching at step 2 with time for detaching suggests that it is easier to attach a token than to detach it. This matches our initial impressions.

We acknowledge the limited ecological validity of these observations as they come from the authors themselves. These results cannot be generalized to average users. However, they give an indication of the performance envelope [11], i.e., the performance that expert users can reach.

### 4 INTERACTING WITH WALL DISPLAYS: WALLTOKENS VS TOUCH GESTURES

WallTokens can act as controllers on a wall display for, e.g., manipulating virtual objects or adjusting parameter values. We believe that they can be an efficient alternative to touch gestures when interacting with a wall from close distance. In this second experiment, we evaluate the performance of WallTokens when they are used as controllers on a wall display.

We hypothesize that WallToken manipulations are more efficient controllers on a wall display than touch gestures are. First, previous studies have shown that users are more accurate with tangibles than with bare finger input [15, 45]. We thus hypothesize that users will be faster with WallTokens than with touch gestures ($H_1$). Second, we hypothesize that a WallToken is more comfortable than touch gestures are for continuous manipulations ($H_2$). This is not only because of the felt under their feet that reduces friction with the wall, but also because of the possibility for users to reposition their fingers on the token while manipulating it. Finally, we also hypothesize that WallTokens’ relative advantage will be lower when manipulating small virtual objects which are under their base than when manipulating large virtual objects ($H_3$). This is because tangibles cause more occlusion than bare hand gestures.
4.4 Design and procedure

Factors. Our experiment involves the following three primary factors:

- **INPUT ∈ \{Token, Touch\}**. The **WallToken** used in the **Token** condition was a red 9.4 cm-diameter circle. We chose a circle shape so that the amount of occlusion does not depend on the token’s orientation. In the **Touch** condition, users perform 2-finger gestures to control both position (i.e., middle of the 2-finger segment) and orientation (i.e., orientation of the 2-finger segment).

- **SIZE ∈ \{Small, Medium or Large\}**. This controls the relative size of the **Modulus** relative to that of the token, and thus the amount of occlusion caused by the token (i.e., the smaller the object, the greater the occlusion caused by the token). **Small** (resp. **Large**) means that the **Modulus**’ diameter is half (resp. twice) that of the token, and **Medium** means that the **Modulus** and the token have the same size.

- **ROTATION ∈ \{0°, -90°, 90° and 180°\}** corresponds to the **Stimulus’** orientation.

The fourth factor, **DIRECTION**, is a secondary one that we introduced for ecological purposes. It specifies how the **Stimulus** is displayed relative to the **Modulus** when the task starts. It can take the following four cardinal directions: **NW**, **NE**, **SW** or **SE**. When the task starts, the **Modulus** is displayed within users’ arm reach (within a 39 cm square at 1.05 m height), and oriented along the y-axis. Its precise location depends on the value of **DIRECTION** in order to ensure that both objects are displayed in the same screen. This is to avoid users having to cross bezels between the wall’s screen cells, as they are an artifact of the specific wall prototype we use in this experiment. The distance between the **Modulus** and **Stimulus** is always 30 cm, but their relative positions depend on **DIRECTION**.

**Design.** Trials are blocked by **INPUT**. Each block contains three sub-blocks, one per **SIZE**. Each sub-block consists of 32 trials, i.e., each **DIRECTION × ROTATION** combination, and is replicated twice. Presentation order of block is counterbalanced across participants, and presentation order of series of sub-blocks is counterbalanced across participants and **INPUT** conditions. Within a sub-block, trials are presented in a random order. This design results in 2304 trials in total: 12 participants × 2 **INPUT** × 3 **SIZE** × 4 **DIRECTION** × 4 **ROTATION** × 2 replications.

**Measures.** We collect the following measures: 1) **Time**, the task completion time (i.e., the timer starts as soon as the token or two fingers touch the wall and stops when the 1.5 s dwell ends); 2) **clutchActions**, the number of times the token or participants’ fingers leave the wall during the task; and 3) the **Modulus’** position and orientation at each input event.

**Procedure.** Participants first sign a consent form. They then stand in front of the wall at a distance of about 45 cm from it. The operator gives instructions for completing a task.

Each **INPUT** block is preceded by three practice sub-blocks, one per **SIZE**, with each sub-block containing four trials (i.e., four **DIRECTION × ROTATION** conditions randomly taken out of the sixteen combinations). Participants can request to do the practice session again if they do not feel comfortable enough. They then complete...
the 97 logged tasks of the first INPUT block. Before proceeding to the second block, they have to sit and rest their arm until they do not feel any more fatigue. In all cases, the break cannot be shorter than one minute.

At the end of the experiment, participants fill in a questionnaire where they grade on a 5-point Likert scale each INPUT along the following aspects: physical demand, mental demand, comfort, performance and occlusion. They then have to circle their preferred INPUT technique for each SIZE condition and overall. The result supports also collects participants’ informal feedback during this debriefing phase. The whole procedure lasts about 45 minutes.

4.5 Results

**Completion Time.** We first analyze the effect of our primary factors on completion time (Time) using a repeated measures ANOVA for the model INPUT × ROTATION × SIZE. and Bonferroni-Holm corrected paired post-hoc t-tests. Figure 6 illustrates our results.

First, INPUT has a significant effect ($F_{1,31} = 35.5$, $p < 0.001$, $η_p^2 = 0.17$), with all participants being consistently faster with **Token**, and **Token** being about 26% faster than **Touch** on average. The result supports $H_1$ (i.e., users are faster with WallTokens than with touch gestures).

We also observe a significant effect of ROTATION on Time ($F_{3,33} = 56.2$, $p < 0.001$, $η_p^2 = 0.33$). Unsurprisingly, participants were significantly faster in the translation-only condition (0°) than in all other conditions (−90°, 90° and 180°, all $p' < 0.001$). However, there is no significant difference between conditions −90°, 90° and 180° ($p' > 0.4$).

Interestingly, there is a significant INPUT × ROTATION interaction on Time ($F_{3,33} = 6.78$, $p = 0.001$, $η_p^2 = 0.04$). As Figure 6-(a) illustrates, the −90°, 90° and 180° conditions are not significantly different in the **Token** condition, while participants have been significantly faster with −90° rotations than with 180° rotations in the **Touch** condition ($p = 0.016$, and no significant difference between pairs <90°,180°> and <90°,−90°>). This is consistent with previous experiments (experiment 2 in [52], and lateral condition in [17]) where participants were faster for clockwise rotations (−90°) than for counterclockwise rotations (90°) with touch gestures. This might be because of a lower cost of movement planning [37] for right-handed users for clockwise rotations than for counterclockwise rotations. In comparison, WallTokens are less sensitive to differences in orientations. This results in **Token** being faster in all conditions, but not significantly in the −90° condition ($p = 0.072$).

Finally, there is a significant effect of SIZE on Time ($F_{2,22} = 7.79$, $p = 0.003$, $η_p^2 = 0.03$), with participants being significantly slower with **Small** than they were with both **Medium** and **Large** ($p' < 0.015$). This suggests that occlusion caused performance issues for **Small** targets. However, contrary to what we hypothesized, the interaction INPUT × SIZE is not significant ($F_{2,22} = 2.29$, $p = 0.124$, $η_p^2 = 0.01$). Even more surprising, not only were participants significantly faster with **Token** than with **Touch** for all SIZE conditions ($p < 0.001$ for **Small** and **Medium**, $p = 0.014$ for **Large**), but they seem to have been even more relatively faster when they had to manipulate small-sized objects (Cohen’s $d = 1.39$ for **Small**, $d = 0.99$ for **Medium** and $d = 0.91$ for **Large**). These results reject $H_2$: occlusion issues are not more detrimental with WallTokens than they are with touch gestures.

**Clutching.** Our second measure, clutchActions, gets incremented each time either the fingers or the token loose contact with the wall during a task (i.e., they clutch to adopt a more comfortable posture in order to keep on controlling). As collected data do not follow a normal distribution, we use paired Wilcoxon signed rank tests for statistical analyses.

The average number of clutch actions is significantly lower in the **Token** condition than in the **Touch** condition (0.11 ± 0.04 vs 0.88 ± 0.16, $p < 0.001$), and this difference is consistent across different ROTATION conditions ($p' < 0.003$) and SIZE conditions ($p' < 0.002$).

Interestingly, clutchActions hardly varies between the different SIZE levels in the **Token** condition ($p' > 0.41$), while it significantly grows when SIZE decreases in the **Touch** condition (from 0.68 ± 0.25 to 1.11 ± 0.33 with significant difference between **Small** and **Medium** and **Large**, $p' < 0.027$). This increasing need for repositioning their fingers with small objects might explain the relative disadvantage of touch gestures compared to tokens that gets higher in the SIZE=**Small** condition. Similarly, there is no significant difference in clutchActions between the different ROTATION levels for
Token, while some differences are significant for Touch. clutchActions is significantly lower for 0° (0.29 ± 0.18) than for the other rotation levels (p’ < 0.004, 0.84 ± 0.30 for −90°, 1.05 ± 0.39 for 90°, and 1.32 ± 0.36 for 180°), and −90° has also significantly less clutchActions than 180° (p=0.009). Here again, this seems to be related to time performance as 0° and −90° are the conditions where participants performed best for Touch. Overall, the need for finger repositioning in the Touch condition seems to have a negative impact on users’ performance. In comparison, WallTokens allow users to reposition their fingers individually on the token while keeping it in contact with the wall, allowing more fluidity in control.

**Integrity & Simultaneity.** A movement that affects several dimensions (here translation and rotation) is integral if the movement can concurrently modify the value of the different dimensions [19]. Integrity gives an indication of the fluidity in the control of several dimensions, and is thus interesting for comparing touch gestures and token manipulations at a fine-grained level. There is no standard way to measure integrity. Here, we adapt the method from [19] with recommendations from [32] by considering as integral a portion of movement where both dimensions change simultaneously to get closer to their target values. Our Integral measure is thus the percentage of movement time during which the differences in position and orientation between the stimulus and the modulus decrease each by more than a given threshold \(th\), or these differences are both very small (i.e., the movement is stable as is typically the case during clutching actions and small adjustments at the end of the movement).

The steps for computing Integral are as follows:
- we consider the movement from the trial start time to the first time the docking conditions are met (dwell start time), and segment it into 10 ms intervals. For each interval, we compute the difference in position and orientation, \(\Delta_{pos}\) and \(\Delta_{orient}\) (normalized in [0, 1]);
- we smooth data to remove sensor noise (using R’s smooth.spline function with default parameters);
- we classify each interval as: (i) integral: \(\Delta_{pos} \geq \Delta_{orient} \geq \Delta_{th}\); (ii) stable: \(-\Delta_{th} < \Delta_{pos} < \Delta_{th}\) and \(-\Delta_{th} < \Delta_{orient} < \Delta_{th}\); (iii) separate: neither integral nor stable;
- then, we compute the percentage of stable and integral intervals among all intervals.

With \(\Delta_{th}=0.001\) (0.1% of the movement amplitude), the average values for Integral are 41.9% ± 1.3 for Token and 29.8% ± 1.2 for Touch. The difference is significant (\(p<0.001\)), as differences per positive rotation condition are. This suggests that WallTokens enable manipulations that are more fluid than touch gestures do, allowing users to manipulate position and orientation in an integral movement.

**Qualitative Feedback.** Figure 7 reports participants’ qualitative feedback by INPUT. In the final questionnaire, they had to give grades for: comfort, mental demand, occlusion issues, perceived performance and physical demand. We compare these 5-point grades with paired Wilcoxon signed-rank tests.

Token receives better scores regarding comfort (\(p=0.002\)) and physical demand (\(p=0.008\)). This supports \(H_2\) (i.e., WallTokens are more comfortable than touch gestures are for continuous manipulations). Touch actually causes more friction and clutching actions than Token does. Furthermore, touch detection through optical technology (such as the infrared frame on our wall) can cause more discomfort

![Figure 7: Distribution of grades (on 5-point Likert scales) for each INPUT along the dimensions: Comfort, Mental Demand, Occlusion Issues, Perceived Performance and Physical Demand (positive assessments are green and on the right).](image-url)
To facilitate the development of applications involving Tangibles can play a lot of roles when interacting with a digital surface. They can materialize users, data and actions to act as identifiers, containers, filters, queries, commands, etc. Many of these different roles are particularly relevant when interacting with a wall display. First, as our experiment above suggests, tangibles can act as controllers when interacting with a wall within arm’s reach. They can act as specialized controllers, freeing users from having to learn complex touch gestures. They can also be used for moving content between distant locations using pick-and-drop interactions [40, 48]. Second, tangibles are particularly useful in collaborative contexts. For example, associating each user with a specific tangible is a low-cost and robust way of identifying individual users (as in, e.g., [51]). This user identification method avoids relying on external optical systems, which are usually costly and vulnerable to occlusion issues that frequently occur in an environment where users physically move around. Moreover, tangibles avoid direct touch with the surface, and can thus limit potential sanitary issues when multiple users interact with it. Finally, wall displays are very large surfaces that raise challenges regarding workspace management. Tangibles can help in that regard as they can be used to mark specific positions. For example, they can be used for tagging personal areas as opposed to shared areas, or for bookmarking positions of interest.

5 APPLICATIONS

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5.1 Development Framework

To facilitate the development of applications involving WallTokens, we have developed a framework based on TUIO\(^6\) [24], a widely used protocol for programming Tangible User Interfaces. Client libraries for TUIO are available in most programming languages (C++, C#, Java, etc.). They connect to an input server and dispatch events according to the TUIO protocol, i.e., in the form of messages that consist of one action among \{down, up\}, as described above, or it can downgrade these events into objects + blobs. In order to also support any programming language, we developed a WallToken TUIO server that any application can connect to in order to receive enriched TUIO events. As illustrated in Figure 8, this server can either dispatch WallToken events as described above, or it can downgrade these events into objects + blobs or, even simple TuioCursor events. Such a downgrade makes it possible to run any existing TUO-based application with WallTokens without modifying its source code. For instance, the Map application described in the next section was anterior to the WallTokens project. It was developed in Java with input based in part on touch TuioCursors. In order to enable WallToken input, we first ran the server in downgraded mode so that the WallTokens are considered as simple TuioCursors. This enabled WallToken input without writing any single line of code. We then progressively added callbacks specific to TuioTokens in order to handle events such as token rotations and attachments.

5.2 Demo Applications

We used the framework described above to develop three demo applications (Figure 9): a picture classification application (Picture); a map application (Map); and an artistic demo (Art). The Picture application displays a collection of pictures for users to classify by grouping them spatially. Large vertical displays are actually good at supporting the classification, grouping and comparison of visual components [20, 31, 39]. The Map application is a multiscale interface that allows users to pan & zoom a large map and instantiate multiple DragMags [49] to magnify specific areas. Finally, the Art application displays a water texture on the entire wall and lets users generate waves interactively, creating an aesthetically-pleasing rendering. This art demo was inspired by the ReactTable [23], which combines tangibles and a tabletop into an electronic instrument for collaborative musical performances.

Rather than providing a full description of each of these applications, we list below some of the roles that WallTokens play in them:

- **WallTokens as data containers.** In the Picture (resp. Map) application, a WallToken can be used to pick-and-drop [40] a picture (resp. a DragMag) from one location to the other. Pick-and-drop interactions are particularly important with large displays as dragging an object over a long distance quickly causes discomfort.

- **WallTokens as controllers.** In the Map application, sliding a WallToken pans the map while rotating it adjusts the zoom factor. Depending on the WallToken’s location, such pan & zoom operations apply to the whole map or are restricted to a specific area.

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\(^6\)https://www.tuio.org/
DragMag. In the Art demo, users can attach a WallToken to the wall to make water drops fall on the large water surface, and then rotate it to adjust the frequency at which drops fall.

- **WallTokens as cursors.** In the Picture application, users can perform drag-and-drop operations to adjust a picture’s position. In the Art demo, users can drag a WallToken to cut through the water surface and generate waves.

- **WallTokens as bookmarks or pins.** Attaching a WallToken to the wall in the Picture application lets users change how they populate selections. Once attached to the wall, a finger swipe gesture that is initiated on a picture and oriented toward a WallToken actually adds the picture to the selection that is associated with that token. In the Map application, attaching a WallToken to a DragMag locks it. This is useful to, e.g., prevent any other user from interacting with a DragMag or simply acts as a salient cue that facilitates later access to it. As mentioned above, in the Art application, users can also pin a WallToken to create a source of water drops.

- **WallTokens as identifiers.** In the Picture application, each WallToken is associated with a distinct selection. Users can add or remove a picture from a selection by tapping it with the associated WallToken. Performing a zigzag sliding gesture with a WallToken clears the associated selection. As a WallToken is uniquely identified, multiple selections do not conflict with each other, making it easy to manage several selections concurrently. In the Map application, users perform a tap with a WallToken on a DragMag in order to pair them. Once paired, the WallToken acts as a proxy to the DragMag, allowing users to manipulate it from anywhere on the wall.

- **WallTokens as collaborative tools.** In the Picture application, WallTokens can be used to implement a range of multi-user contexts. In a competitive context, each user can have their own set of tokens in order to compare individual performance. In a collaborative context, users can work on different regions towards a shared goal, exchanging tokens if needed. As they are uniquely identified, WallTokens also enable concurrent pick-and-drop operations from multiple users. A WallToken can even be duplicated to enable multi-user pick-and-drop where one user picks a picture and the other drops it [29].

We chose this specific set of demo applications as they highlight the unique advantages of large vertical displays: in the Picture application, users can step away from the wall in order to view many pictures at once; in the Map application, several users can concurrently work with a map displayed in its preferred orientation; and in the Art application, the performer can share their creative space with a potentially large audience.

## 6 LIMITATIONS

**Expressive power.** In our study, WallTokens had advantages over touch gestures in terms of efficiency and comfort. But a single WallToken has three degrees of freedom only (2D translation and rotation), while touch gestures can control more degrees of freedom (e.g., pinch to scale). When more degrees of freedom are needed, a combination of touch gestures and tangibles could be interesting (e.g., holding a finger still, close to the token, to switch between rotate and scale modes, or sliding a finger towards or away from the token to control scale). This could avoid users experiencing difficulties when performing multi-touch gestures for the integral control of several dimensions, when they want to act on one dimension without affecting the others [35]. We could also think of more elaborate token designs with e.g., an adjustable cursor as in [43], to increase the number of degrees of freedom that a token can control.

**Passive tokens.** Our WallTokens are fully passive so as to make them compatible with any active display technology. Their mechanism relies on basic supplies only (suction cup and spring). As people are familiar with such supplies, we expect WallTokens to afford their manipulations. One first limitation of suction cups is that they work only on smooth surfaces. But this should not be a major issue with most display technologies, as these generally emit light and thus have flat, smooth surfaces to avoid any diffraction effect. A second limitation is that WallTokens require an additional action with the push-handle in comparison with approaches based on magnets on a projection-based whiteboard [26]. However, this extra action, which we estimate to take less than 1s in our first experiment, makes WallTokens harmless to any active screen technology as opposed to magnets that would damage electronics in screens.

## 7 CONCLUSION AND FUTURE WORK

We contribute WallTokens, which enable tangible user interfaces on vertical displays. WallTokens’ low-cost design combined with our development framework make it possible to prototype applications...
that involve multiple tokens. Not only can users manipulate those tokens on the wall, they can also attach them to, and detach them from it at will. This opens up a design space for applications based on multi-token input that could only run on horizontal surfaces until now (e.g., [22, 23]). As users do not have to keep on holding tokens, our contribution also makes tangible input easy to combine with other input channels such as finger touch or pointing devices on vertical displays. Future work includes the design of such interaction techniques that actually combine tangibles with other modalities. We also plan to refine the design of WallTokens to track their position and orientation when users hold them in the air, as recently proposed with the concept of Off-Surface Tangibles [7], in order to make it possible for users to rely on WallTokens for distant interactions with the wall.

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SUPPLEMENTAL MATERIAL
Details on WallTokens fabrication (e.g., SDF files for the different components), experimental data, and the source code of the development framework are available both as supplemental material and online at https://walltokens.lisn.upsaclay.fr.

REFERENCES