Characteristics of Conductive Paints and Tapes for Interactive Murals

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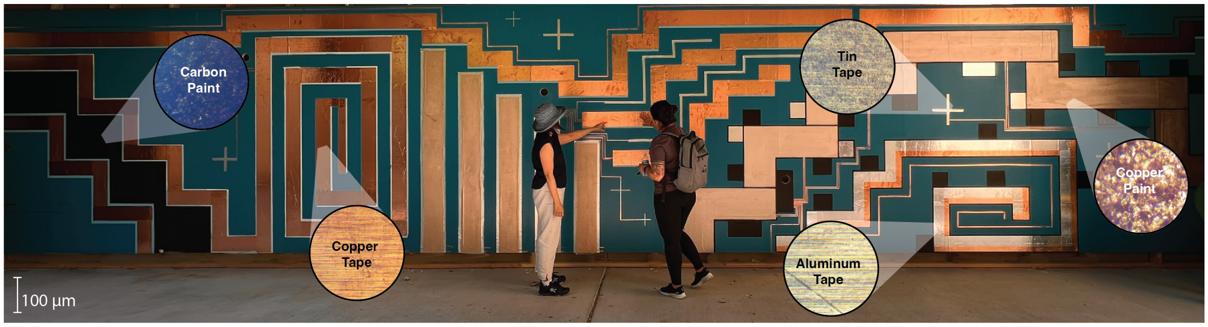

Fig. 1. An Interactive Mural that uses conductive paints and tapes for both functional and aesthetic purposes. Materials are used as capacitive touch sensors as well as visual design elements. This 44 × 10 foot (13.5 × 3 m) mural is permanently installed outdoors. The scale in the lower left hand corner applies to all microscopic images of materials, shown in circles.

This paper analyzes a collection of conductive paints and tapes. We describe and compare their electrical conductivity, durability, appearance, and cost. We investigate different means of connecting these materials to each other and other electronic components–including connection via solder, conductive epoxy, conductive adhesives, and metal mechanical fasteners. We explore different means of insulating and protecting materials and provide the results of a range of durability tests. The results are discussed in the context of the development of interactive murals–large outdoor interactive surfaces that are intended to function for years. We identify two conductive paints, CuPro-Cote and Silver/Copper Super Shield, and two conductive tapes, Copper and Tin that are highly conductive, stable across most of our testing conditions and, we believe, suitable for interactive murals.

CCS Concepts: • **Human-centered computing → Interaction design process and methods**.

Additional Key Words and Phrases: conductive paint, conductive tape, materials, interactive murals

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1 INTRODUCTION

Conductive paints, inks, and tapes have been widely used in Human-Computer Interaction (HCI) and Ubiquitous Computing research to build novel interfaces. These materials have enabled researchers to create paper-based

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technologies[46, 52], printed devices [32], large scale interfaces [11, 59], novel wearables [31, 39], and assistive devices [9]. Conductive surface treatments enable and afford new ways of working and new contexts for technology design [12]. They are a significant and, importantly, generative material for many designers.

However, basic properties of many of these materials, including conductivity in different use scenarios and durability, are often unknown. Designers typically use these materials in ways not intended by their manufacturers. For instance, most conductive paints and tapes were developed for electromagnetic shielding purposes, but designers have used them to build circuits [40], sensors [56, 61], generators [22], and antennas [15]. This means that the information published by manufacturers about the materials often does not describe the most important characteristics of the material for its use in an interface application. We seek to identify materials and techniques that can be used to build robust wall-based interfaces that can withstand extended real-world use.

The paper's primary contribution is a detailed comparative and long-term (two year) analysis of four conductive paints and five conductive tapes along with a range of electrical connection techniques. We identify two paints (CuPro-Cote [37] and Silver/Copper Super Shield [19]) and two tapes (Copper [2, 8] and Tin [5]) with low resistance that are stable across all or most of our test conditions including water immersion, freezing, and exposure to rain, hail, and extended sunlight. Durable connection techniques include painting over tape (with CuPro-Cote or Silver/Copper Super Shield) and soldering. We also discuss the successful use of several materials and connection methods in two outdoor interactive murals–murals that contain embedded electronics–that remain fully functional years after their construction.

2 RELATED WORK

2.1 Novel Conductive Materials

Many researchers have worked with non-traditional conductive materials to build interactive surfaces. Construction methods that employ conductive ink and paint include inkjet printing, screen printing, hydrography, spray painting, and brush painting. Researchers have also created circuits and sensors from conductive tapes, metal foils, and specialized paper. Table 1 provides a summary of recent work in material-based electronic design [1].

Many researchers who have developed material-focused tools have explored material characteristics as part of larger research efforts. For instance, Kawahara et al. provide detailed information about the conductivity of the silver inks they used to develop their low-cost inkjet circuit-board printer [32]. Cheng et al., who developed a technique for printing circuits in silver ink and then transferring these circuits to tapes, provide detailed analyses of the behavior of different tapes they constructed under different conditions [24]. Zheng et al., who developed methods for using carbon-based paper to create a range of novel sensors, present similarly detailed information about material properties [61]. Kao et al. describe the conductivity, durability, and wearability of a range of foil-based materials including copper tape and gold leaf in their work developing skin-based devices [31].

Shorter et al.'s Practical Notes on Paper Circuits provides a more general comparative analysis of seven different conductive paints and inks [53]. This survey includes cost and manufacturer supplied surface resistance. The authors also provide information on connection method, demonstrating how electronics can be attached to painted or printed materials using paper clips, conductive epoxy, paint, and tape. The paper is a useful DIY reference, but it provides limited technical information. Material information from manufacturers is collected and presented, but not tested. Some connection methods and construction techniques are demonstrated, but none are tested and the survey does not include information about the durability of materials or connection methods. Most of the connection techniques presented are suitable only for quick proof-of-concept prototyping.

Our work is distinguished by material-based research that is focused on *long-term durability and real-world use*. Previous material characterization has focused on short term features like paint application and immediate interface construction. We explore features critical for long term use: 1) change in material conductivity in

[1]We do not include related work in electronic textiles since that is a distinct discipline with different application considerations.

Material	Technique	Research
Conductive Inks	Inkjet Printing	Pourjafarian et al. [44], Cheng et al.[24] Gong et al. [28] Kawahara et al. [32]
Conductive Inks	Screen Printing	Liu et al. [38], He et al.[30]
Conductive Inks	Hydrography	Groeger et al. [29], Saada et al. [49]
Conductive Inks and Paints	Spray Painting	Zhang et al. [59], Wessely et al. [57]
Conductive Paints	Brushing	Mellis et al. [40], Buechley et al.[10], Zheng et al. [60]
Copper Tape	Tape Application	Qi et al [47, 48], Umetani et al. [55]
Gold Leaf, Metal Leaf	Adhesive Application	Segawa et al. [51], Kao et al. [31] Saul et al. [50]
Carbon Paper	Folding	Zheng et al. [61]

Table 1. A summary of recent research in Ubiquitous Computing that employs novel conductive materials

different contexts and over time and 2) durability of connection methods in different contexts and over time. Some of our results are predictable–ie: soldered connections are highly durable–but others, including the properties of different conductive paints and adhesives, are more unexpected. This foundational work is enabling us to build novel interfaces like interactive murals and test them in new ways–in the wild over long periods of time.

2.2 Wall-Based Interfaces

Interactive Murals are a wall-based interface, a category of growing interest in the Ubiquitous Computing community. Wall-based interfaces provide unique opportunities to embed sensors and actuators into the built environment. They also support new modes of interaction, including the ability to detect and respond to large-scale bodily movement and the ability to support large-scale collaborative interaction.

Zhang et al.'s Wall++ consists of a wall with painted capacitive sensing electrodes that can detect full-body motion [59]. The team used a roller to paint two layers of electrodes onto a 12 × 8 foot (3.6 × 2.4 m) wall with water-based Nickel Super Shield paint [18]. The sensing array was then covered with traditional house paint to conceal it. In the course of this work the researchers compared the conductivity of four conductive paints applied to different substrates via brushing, rolling, and spraying.

Wesseley et al. propose using an airbrush to spray conductive ink and paint onto a variety of surfaces, including walls. Their material-based testing was focused on how conductive inks and paints are absorbed by different surfaces including stone, ceramic, wood, and cardboard [57]. Cheng et al developed a small robotic plotter DUCO designed to apply circuitry to walls [23]. Their plotter, which is hung from a wall, employs a specialized pen filled with conductive ink to draw circuits. Qi developed beautiful large-scale interactive electronic paintings that were constructed from paper, copper tape, and standard electronic components [45, 48]. Buechley et al. built large sheets of "interactive wallpaper" using conductive and non-conductive paints [11].

Our work is similarly motivated by an interest in exploring the unique interaction possibilities presented by walls. Interactive murals are distinct as also serving as pieces of community-situated public art. We are motivated by social and cultural interests as well as technical ones. We believe interactive murals can be connected to and

Fig. 2. Detail from an interactive mural that uses copper tape and CuPro-Cote. Left: During construction circuits are made with copper tape and touch sensors are painted with CuPro-Cote. Electrical connections between materials are made by painting conductive paint over copper tape. Right: The circuitry and touch sensor have been painted over with non-conductive paint. Touching the lady bug activates different light patterns. This mural is 32 feet wide by 10 feet tall (10×3 m).

enriched by traditions of community mural painting, in which artist collaborate with youth to create beautiful pieces that often celebrate marginalized communities [36, 54]. We are exploring how interactive mural projects can engage youth in STE(A)M by building off of their existing interest and expertise in the arts. We are designing activities that involve constructing interactive murals to introduce youth to electronics and programming. We are also interested in engaging diverse young people in an authentic research experience as we collaboratively explore technical and interaction design challenges, guided by participatory design methods [26, 41].

3 MATERIALS

This study is motivated by our interest in identifying conductive materials suitable for building interactive murals–large-scale painted interactive surfaces with embedded circuitry that are outdoor, long-term installations, see Figures 1 and 2 [13, 14]. A mural may be applied to a wide range of surfaces including masonry, stucco, wood, and drywall. In most cases, we are not able to hide electronics behind a wall; all circuitry and components must be applied *to the surface of the wall.* The ideal conductive materials for our application are flat, easy to apply, and have high conductivity that remains stable across a range of conditions, including exposure to sunlight, water, hot and cold temperatures, and human touch. Our interactive murals are constructed collaboratively with a mural artist and middle and high-school students. This context imposes additional constraints. We want materials that are non-toxic, easy to apply, and, as much as possible, we want to integrate them into traditional mural painting practices.

Suitable materials should: 1) be easy to obtain and reasonably priced, 2) not pose significant health or environmental risks, and 3) not change the character of a wall's surface. We are not interested in materials like wires which would need to be attached to walls with either glue or mechanical fasteners and would change the surface texture of a wall. We therefore focus on flat materials that can be applied either via an integrated adhesive (in the case of tapes) or with a paint brush (in the case of paints). All of the materials we consider are currently available from retail suppliers and are easy to apply to surfaces. We do not consider spray-on materials, which require the use of protective equipment like respirators [57].

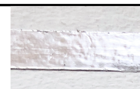
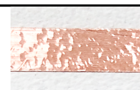
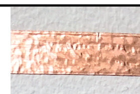
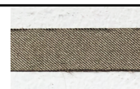
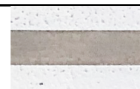
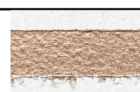
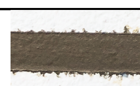
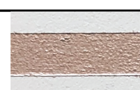
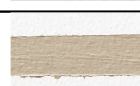
Tape	**Image**	**Surface Resistance ($\Omega/\square$)**	**Cost $\$/m^2$**	**Safety Rating**	**Further Study?**
Aluminumm, cond. adhesive, 3M 1170 [1]		.010	$176	0	yes
Aluminum (HVAC) [4]		.010	$5	0	yes
Copper, cond. adhesive, 3M 1181 [2]		.005	$157	0	yes
Copper, generic [8]		.005	$44	0	yes
Nickel Fabric Tape [27]		.100	$103	0	no
Tin, cond. adhesive, 3M 1183 [5]		.005	$169	0	yes
Paint	**Image**	**Surface Resistance ($\Omega/\square$)**	**Cost $\$/m^2$**	**Safety Rating**	**Further Study?**
Carbon, Bare Conductive [25]		55.0	$69	0	no
Carbon, YShield [58]		10.0	$9	0	yes
Copper, CuPro-Cote [37]		.100	$28	1	yes
Nickel Super Shield [18]		1.30	$85	2	yes
Silver/Copper Super Shield [21]		.020	$94	2	yes
Silver Super Shield [19]		.002	$456	2	yes

Table 2. Materials considered. Resistance information provided by manufacturer. Safety Rating is on a scale from 0 (safe) to 5 (hazardous). Note: resistance given for 50micron (2mil) layer for all paints.

Other flat materials that we did not consider include conductive fabrics, conductive foils (ie: gold and other leafs and aluminum foil), which are more challenging to adhere to surfaces [31, 51], inks that are designed for screen, inkjet, or laserjet printing–which cannot be easily painted onto walls–and materials known to be highly toxic, like lead tapes.

Table 2 lists the materials we initially considered. For each candidate material, we collected its surface resistance, as provided by the manufacturer, and calculated its cost per square meter of coverage. We also surveyed Safety Data Sheets (SDSs) for basic safety information. The table indicates, on a scale of 0 (safe) to 5 (hazardous) how potentially harmful the material is to human health and/or the environment. The table also indicates the materials that were chosen for further study.

3.1 Tapes

Metal foil tapes consist of a thin sheet of metal attached to an adhesive. Tapes labeled conductive adhesive in Table 2 are explicitly marketed as having a conductive pressure sensitive adhesive [1, 2, 5]. While the manufacturer (3M) does not provide information about the conductive adhesive, we believe it may be "Z-tape" [7]. It is translucent, unlike 3M's XYZ tape [6] and behaves similarly to Z-tape in the tests we have conducted. Tapes referred to in this paper as "generic" make no claims about their adhesive being conductive.

Metal foil tapes are highly conductive and easy to apply to different surfaces. The copper, aluminum, and tin metal foil tapes are more conductive than any of the paints or fabric-based tapes we considered. Copper tape, which is frequently used to build paper circuits [47], is solderable, as is the tin tape. Aluminum tape cannot be soldered. However, Aluminum HVAC tape is the cheapest material on our list. It is also corrosion resistant and available in most home improvement stores.

The copper tape is a bright copper in appearance, the tin a dull dark silver, and the aluminum a bright pale silver. The appearance of different materials is significant. In some of our projects, we employ materials for decorative as well as functional purposes, see Figures 1 and 3. All of these tapes were selected for future investigation. We chose to investigate varieties with conductive and generic adhesives. The materials without conductive adhesives are significantly less expensive, but we wanted to determine if the electrical connection provided by conductive adhesives could be worth the expense in our intended applications.

The fabric tape consists of a nickel-plated fabric attached to an adhesive [27]. This tape was eliminated from future study for a few reasons. First, the wall-based applications we are most interested in exploring in do not require ongoing flexibility–walls may be curved, but are not repeatedly bent. This tape is not as conductive as the metal foil tapes and is not easily solderable. It is also significantly more expensive than the metal foil tapes. We did not consider other similar conductive fabric tapes [3, 34] for the same reasons. Other tapes that we did not consider include carbon fiber tapes, anti-static tapes, and lead tapes.

3.2 Paints

We collected preliminary information for six different paints. These paints can be sorted into two broad categories: carbon-based paints and metal-based paints. The carbon-based paints, Y-Shield [58] and Bare Conductive [25], have a consistency and workability that is similar to non-conductive paints. They are relatively easy to apply while achieving an even layer of paint.

The remaining metal-based paints are comprised of metal particles mixed into a binder. These are more challenging to work with. Metal settles out of the binder material quickly so the paints need to be stirred frequently during use. Metal particles can also settle out of the binder during painting to form lumps on a surface. It is hard to apply the paint consistently and multiple coats are required to establish even coverage across a surface. Within the category of metal-based paints, CuPro-Cote is a water-based paint that can be thinned and cleaned with water [37]. It does not release harmful vapors. However, copper is rated as hazardous to acquatic life and paint can easily end up in water ecosystems during cleaning, which is why CuPro-Cote is given a safety rating of 1 in Table 2.

The Super Shield paints, manufactured by MG Chemicals, are more dangerous to work with. Though marketed and identified as water-based [20] they require cleaning with acetone. (Super Shield Paints are also available in Acrylic and Epoxy-Based varieties [17].) The water-based Super Shield paints release flammable vapors and pose significant health and environmental risks [18, 19, 21]. They are also more expensive than CuPro-Cote. We have found the Super Shield paints slightly easier to apply consistently. The Silver [19] and Silver/Copper [21] paints are rated as more conductive than CuPro-Cote. Note: we will refer to the Silver Coated Copper Super Shield as Silver/Copper throughout the rest of the paper.

Each paint has a distinctive appearance, see Figure 1 and Table 2. The carbon-based paints are a flat black. Once dried, surface abrasions turn a dark silver. The CuPro-Cote and Silver/Copper paints are both a sparkly rose-gold. Silver/Copper is a slightly rosier shade. The Nickel Super Shield [18] is a flat dark grey and the Silver Super Shield [18] is a flat light grey.

Paint is inherently more challenging to test than other materials because of the variability that arises during application, a phenomenon researched here and also in previous work [59]. Paint coverage can change depending on (for example) the brush used, the substrate the paint is applied to [57], the speed of application, and how recently the paint was opened. We explore some of this variability below and control for some of it by including multiple samples in our tests. We also describe our processes of sample production in detail. However, it is important to keep this intrinsic variability in mind when reviewing our results.

None of the paints we researched are as conductive as the metal foil tapes. Though the Silver Super Shield has a lower resistance rating than aluminum tape, in practice for our application contexts, we found that the metal foil tapes are more conductive than any of the paints. Despite being less conductive than tapes, paints provide distinct advantages. Paints can be applied to areas of arbitrary size and shape and do not rely on separate

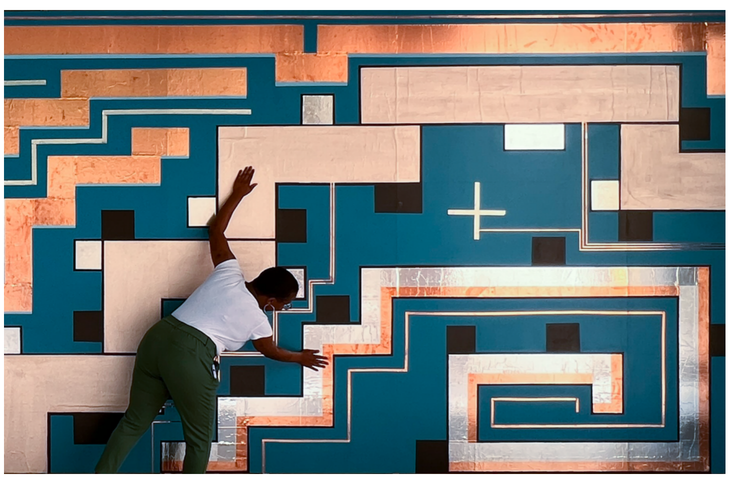


Fig. 3. A detail from a mural that uses several of the materials in our survey for decorative and functional purposes including Copper, Tin, and Aluminum Tape as well as CuPro-Cote (Copper) and YShield (Carbon) Paint. This mural uses the connection methods of soldering (tin, copper tape, and PCB connections), applying paint over tape (paint to tape connections), and mechanical fastening via screws (aluminum to copper tape connections). All conductive surfaces are capacitive touch sensors. Touching a sensor either triggers or modulates sound. This mural is 44 feet wide by 10 feet tall (13.5 × 3m).

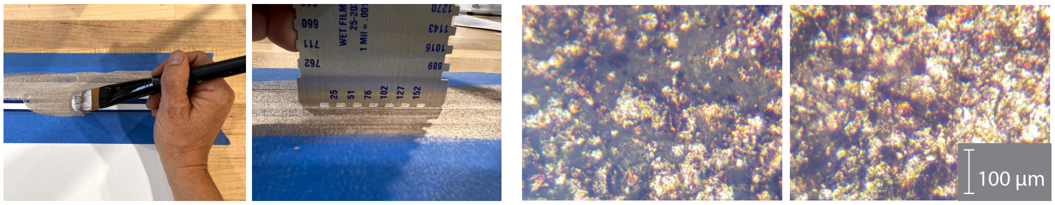


Fig. 4. Paint application process. From left to right: paint application, measuring paint thickness with a wet film thickness comb. Microscopic images of CuPro-Cote: second from right: one coat, right: five coats.

adhesives for connection. They can be integrated into surfaces in a way that tapes cannot. They can also be integrated into the process of painting (on paper, an artifact, or a wall) in ways that other materials cannot.

We eliminated the bare conductive paint from further study because it is both more expensive and less conductive than YShield. There is an assortment of readily available carbon-based paints that we did not include in our tests for similar reasons, including varieties manufactured by MG Chemicals [16]. We eliminated the Silver Super Shield due to its extremely high cost. It may be suitable for small-scale applications, but it is prohibitively expensive for large-scale wall-based applications.

4 CONDUCTIVE AND INSULATING PAINT

4.1 Conductivity of Conductive Paint

We tested conductivity as a function of coats of paint for Silver/Copper, CuPro-Cote, YShield, and Nickel, using a substrate of primed Mural Paper. Paint was applied to primed Mural Paper with a 25mm brush, see Figure 4. Paint was applied across taped stencils to create clean lines. To insure the consistency of paint application, we measured the thickness of each layer for each material using a wet film thickness comb. This device is placed onto the wet paint immediately after application. A thickness measurement is obtained by observing which teeth in the comb–each at a different height–come into contact with the the paint, see Figure 4 second from left. For all materials, each layer was approximately 2 mils (50 um) thick. Our measurements align with available information on recommended paint thickness. In particular, technical datasheets for Silver/Copper and Nickel paints recommend an application thickness between 50 and 65 um (approximately 2 mil) [18, 21].

For each material, we painted three different lines, 6mm wide and 300mm long, in layers ranging from one to five for each material. That is, we painted three lines with one layer of paint, three lines with two layers of paint, and so on up to five layers. We measured the conductivity of each line using a multimeter with probes attached to the ends of each painted line. We calculated the mean and standard deviation of these measurements for each set of samples.

Figure 4 right shows microscopic (10x) images of samples of CuPro-Cote painted with one and five coats that illustrate how conductive particles build up as layers of paint are applied to a surface. Areas of paper can be seen through the copper particles in the left image. In the right image, the surface is completely covered. These differences are undetectable to the naked eye; both surfaces look as though they are completely covered with paint.

Figure 5 shows the results of these paint-layer tests. As would be expected, resistance and variance decrease as a function of painted layers. The largest decrease for all samples is seen in the application of the second coat.

The Silver/Copper and CuPro-Cote are the most conductive paints in our collection. Silver/Copper has an average resistance of 13.4 Ω for one coat and 1.7 Ω for five coats. CuPro-Cote ranges from 26.0 to 1.3 Ω. YShield ranges from 313 to 34 Ω. Nickel Super Shield is the least conductive paint, with a range from 2366 to 63 Ω. Based

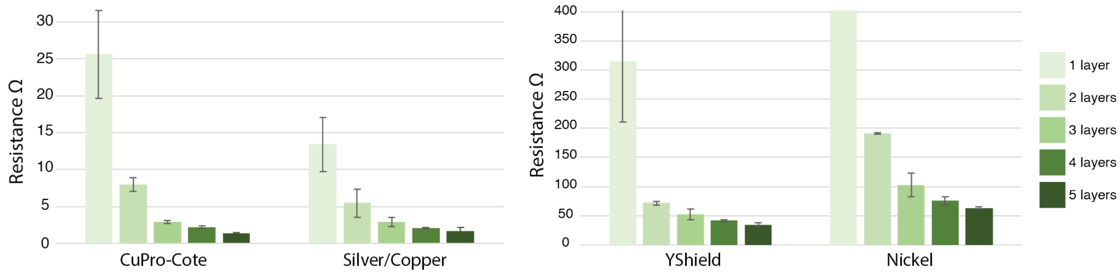


Fig. 5. Resistance as a function of number of layers (1-5) for four different paints. Each layer is approximately 2 mils thick. N=3 for each condition.

on these results, we suggest that at least three layers of paint be used to achieve reliable, predictable conductivity. The remainder of our painted tests are conducted with four layers of paint unless otherwise indicated.

We conducted a second set of tests to better understand the variability and long-term stability of the four paints. We painted ten lines of each material at 6mm (1/4") and 12mm (1/2") wide. All lines were 300mm (12") long and painted with four layers of paint.

Paint	**After Painting**		**Change After Two Years**	
	6mm (Ω)	12mm (Ω)	6mm (Ω)	12mm (Ω)
Silver/Copper	1.9 +/- 0.3	1.3 +/- 0.2	0.0 +/- 0.5	0.0 +/- 0.1
Copper CuPro-Cote	2.3 +/- 0.3	1.1 +/- 0.2	0.1 +/- 0.2	0.1 +/- 0.1
Carbon YShield	36 +/- 2.8	19 +/- 1.9	3.7 +/- 1.8	0.0 +/- 0.9
Nickel Super Shield	84 +/- 21	50 +/- 11	85 +/- 34	34 +/- 17

Table 3. **Material Conductivity**. Average resistance and standard deviation of painted lines, 300mm long × two different widths. Sorted by conductivity. The two right-hand columns show the average change in resistance of the lines. Green cells indicate $< 1\Omega$ of change, yellow $< 5\Omega$, and red $> 20\Omega$. N=10 for each material.

The "After Painting" columns in Table 3 show the results of these tests, with paints sorted by conductivity. Immediately after painting, Silver/Copper is the most conductive paint and Nickel the least. CuPro-Cote and Silver/Copper are significantly more conductive than YShield and Nickel. For all materials, resistance and variance decrease with the width of painted lines. This makes intuitive sense. As surface area increases so does conductivity. The likelihood that any small localized variation in conductivity will dramatically impact the conductivity of the entire sample also decreases as the surface area increases.

The painted samples were then stored for two years and their conductivity was remeasured, see the right-hand columns in Table 3. The samples were stored indoors on a flat shelf inside of a folder. The conductivity of three out of the four materials remained fairly stable over the two year time period. The small changes observed for Silver/Copper and CuPro-Cote are not significant. The resistance for YShield lines increased significantly (10% (p-value .02)) for only the 6mm lines. For both the 6mm and 12mm lines of Nickel paint, the resistance increased sharply. The 6mm Nickel lines experienced a 100% increase (p-value .001), and the 12mm lines a a nearly 70% increase (p-value .001). A gradual darkening of the color of the Nickel paint over time was a visual clue to this degradation. It is well established that Nickel tarnishes in air [33]. While Copper and Silver are similarly subject to oxidation [36], CuPro-Cote and Silver/Copper contain ingredients that inhibit corrosion.

It is clear from these results that Nickel paint is not a viable material to use in long term installations or applications. It is also significant that CuPro-Cote and Silver/Copper are stable conductors over long time periods. These studies also indicate that larger surface areas of paint improve conductivity and lessen variability.

4.2 Insulating Properties of Non-Conductive Paint

When using conductive surface treatments, and conductive paints in particular, it seems reasonable and desirable to use traditional (non-conductive) paint as an insulator. Conductive and non-conductive paints are easy to combine and layer in interactive murals, see Figure 2. However, based on preliminary experiments, it was not clear to us if non-conductive paint can be reliably employed for this purpose. We conducted tests to determine if and when it can.

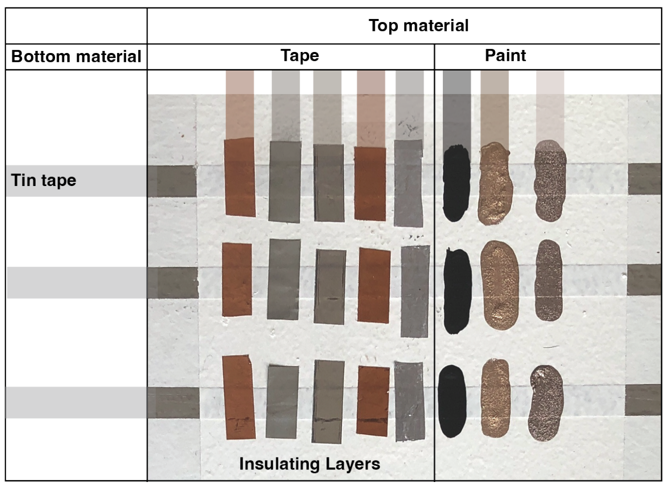


Fig. 6. A bottom layer of Tin tape is coated with two layers of white house paint and then, from left to right: copper tape, tin tape, aluminum tape (conductive adhesive), copper tape, aluminum tape (generic adhesive), YShield, CuPro-Cote, and Silver/Copper. This image shows three samples of the Tin tape, two-paint layer condition.

We created samples to test the insulating properties of non-conductive paint in different scenarios. Sheets of 300mm × 300mm MDF were first painted with a primer. Next, we created three lines, measuring 6mm × 300mm, of each of six conductive materials: copper tape, aluminum tape, tin tape, CuPro-Cote, Silver/Copper, and YShield. We then painted over these lines with (insulating) white house paint, varying the coats from one to six. This paint was applied with a roller. We again used a wet film thickness gauge comb to measure the thickness of these layers, which were, like conductive paint layers, approximately 2 mil thick. Finally, we applied a second conductive layer on the top, testing each possible material combination and each possible insulating configuration, see Figure 6.

There are 48 possible conductive material combinations, six insulating conditions, and three samples for each condition for a total of 864 samples. Figure 6 shows one configuration–a layer of tin tape insulated by two coats of paint. We used a multimeter to detect electrical connections between insulated layers. We determined a sample was adequately insulated only if all three samples for the given configuration, as well as all samples with additional insulating layers, had no electrical connections—that is, the multimeter was unable to obtain a resistance reading between the two materials. Since resistance is a function of electrical current, our results must be understood in the context of low-current applications only.

	Top				
Bottom	Metal tape generic	Metal tape conductive adhesive	YSheild	CuPro-Cote	Silver/Copper
Aluminum tape	1	1	2	2	3
Copper tape	1	1	2	3	4
Tin tape	1	1	2	2	3
YShield	1	3	4	4	5
CuPro-Cote	1	3	4	4	4
Silver/Copper	2	3	5	4	4

Table 4. **Insulating Paint.** Layers of insulating paint required to prevent connection between a bottom material and a top material. Cyan (1-2 layers) = safe to use paint as an insulator, Blue (3 layers) = possible to use paint as an insulator, Pink (4-5 layers) = not recommended to use paint as an insulator.

Our results are summarized in Table 4. This matrix indicates how many layers of house paint were required to create a reliable insulator for each material combination. For example, two layers of house paint were required to insulate a bottom coat of copper tape from a top coat of YShield.

Our experiments indicate that, for metal foil tapes, the only property that is important when used as a bottom coat is the metal variety. The only property that is important when used as a top coat is whether or not the tape has a conductive adhesive. We found that non-conductive paint can function as an insulator between two layers of foil tape and when applying foil tape over conductive paint. In these scenarios, shown in the two left-most columns in the Table, at most three layers of house paint were necessary to insulate materials.

However, we found that extreme caution should be taken when employing paint as an insulator when conductive paint is applied as a top coat, particularly when it is applied over a bottom coat of conductive paint. These scenarios are shown in the three right-most columns of the table, with the dual conductive paint conditions in the lower right hand corner. We also found that visual appearance is not a reliable indication of insulation. That is, a conductive material can visually appear completely covered before it is electrically insulated.

We do not recommend using non-conductive paint as an insulator between any conductive paint layers. We also recommend that non-conductive paint be used as an insulator only in very low-current applications like passive sensing. If traces will be used as general purpose conductors, i.e.: to connect power supplies or actuators in a circuit, non-conductive paint should not be used as an insulator.

5 ELECTRICAL CONNECTIONS

Establishing reliable connections between one material and another can be challenging, as can attaching standard electronic components to different materials. Of the materials we considered, only the copper and tin tapes can be soldered. Other types of connections can be made by painting over connection points with conductive paint, gluing them with conductive epoxy, and attaching them with conductive z-tape [53]. However, there is essentially no published information on the reliability or durability of most of these connection methods. We are interested in determining which types of connections withstand the kinds of stresses that electronics deployed in interactive murals are likely to face.

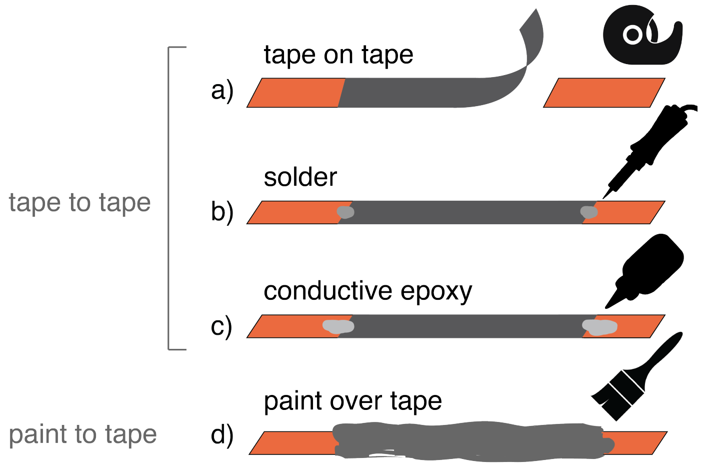


Fig. 7. Four different kinds of connections: a) tape adhesive b) solder c) conductive epoxy, and d) paint. Methods a)-c) are used to make tape to tape connections and method d) is used to make paint to tape connections.

5.1 Test Set-up

To explore these questions, we developed a set of connection methods that employ tape (with both conductive and "generic" adhesives) Figure 7 a), solder b), conductive epoxy c), and paint d). We used methods a)-c) to make connections between different conductive metal foil tapes and method d) to make connections between conductive paints and tapes. We note that this is not an exhaustive survey of all possible connection methods. For instance, we could have tested different paint to paint connections. However, we identified this set of testing conditions as the approaches that seemed most useful for interactive mural applications, where we know we need to make connections between different taped areas, between tape and standard electronic components, and between painted and taped areas.

We developed testing procedures and companion hardware and software that allows us to track conductivity over time. Our testing hardware is based on the Adafruit Adalogger, a SAMD-based microcontroller, with an onboard SD chip. We measure the change in resistance for materials and connections over time using voltage dividers, see Figure 8. Appendix B includes more detailed information about our testing hardware.

Our connection tests were conducted on test strips of primed Mural Paper measuring 80mm (3.5”) wide by 360mm (14”) long. Generic copper tape was applied as a base layer. We tested connections between this base layer and a top material, see Figures 7 and 8. The top material occupied 100mm (4”) in the center of the strip. It was attached to the copper base layer via 6mm of material overhang on either side. That is, tapes and paints were applied 6mm over and on top of the copper base layer on either side of the 100mm to test their connection to the base.

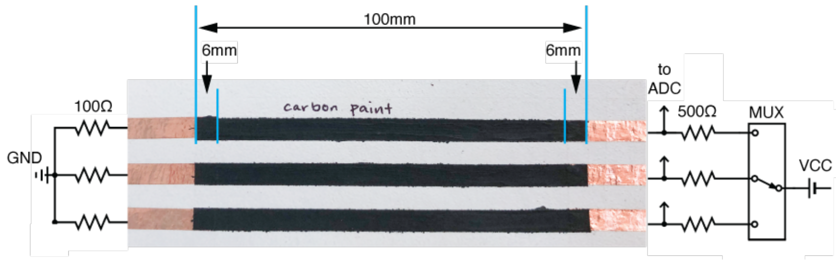


Fig. 8. Our connection test set-up. An example strip with YShield paint and a schematic diagram of the testing hardware. Connection: paint over tape. This diagram also shows important dimensions.

	Solder	**Tape: Conductive**	**Tape: Generic**	**Epoxy**	**Paint**
Aluminum Tape		x		x	
Copper Tape	x	x	x		
Tin Tape	x	x			
YShield Paint					x
CuPro-Cote Paint					x
Silver/Copper Paint					x

Table 5. **Connection Methods**. Connections tested for each material in each test. Connection methods are shown in the top row. "Tape: Conductive" refers to a connection made with a tape with a conductive adhesive. "Tape: Generic" refers to a connection made with a tape with a generic adhesive. (All connections made to bottom layer of copper tape.)

Three identical samples were created for each material/connection. Figure 8 shows a test strip with carbon paint. We tested seven different materials using several different connection techniques. Table 5 shows a chart listing the different materials and connections used for each of the tests described in this section. Unless otherwise noted, each test was conducted on a different (new) sample.

Note that we conducted some initial tests using Aluminum tape with generic adhesive, but found that connections made with this material were not conductive enough to include in further testing. Connections were almost immediately broken in every circumstance we explored.

5.2 Freezing

We are interested in building murals outside where they will be subject to freeze and thaw cycles, so we explored material and connection sensitivity to freezing and thawing. For this test, resistance and temperature measurements were again taken every 500ms. We put samples in a freezer (temperature -5°F) for two hours and then removed them and let them return to room temperature (80°F). Before being placed in the freezer, the samples were left at room temperature for 10 minutes to obtain base readings for resistance and temperature.

This test was designed to provide preliminary information about the behavior of different materials and connections during freeze-thaw cycles. We collected additional information about repeated (real-world) freeze/thaw behavior in our outdoor durability tests, which are described in Section 6.

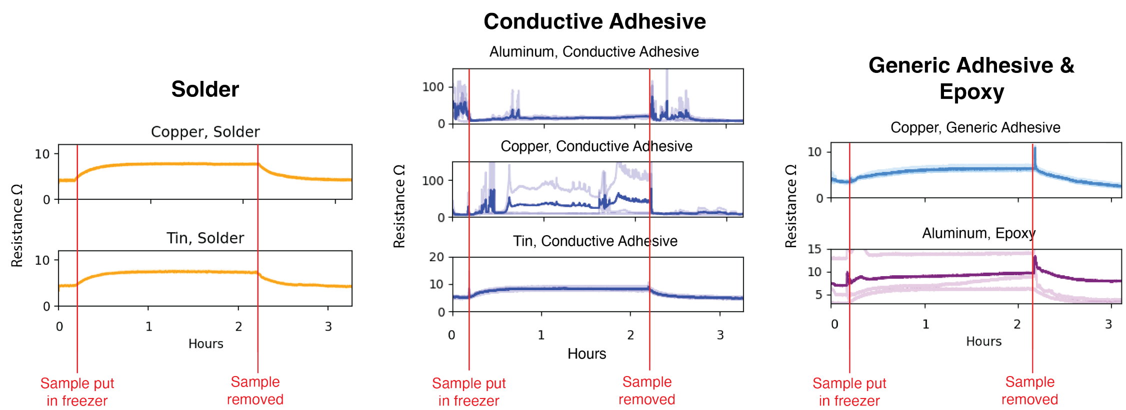


Fig. 9. **Conductive Tape**: Change in resistance due to freezing and thawing. Note that Y-Axis values are different for different materials. Data for individual samples shown in light color, average shown in dark color. N=3 for each condition.

Figure 9 shows the results for conductive tapes. The soldered connections experienced the least amount of change. Most of the tapes attached with conductive adhesive were unstable and exhibited significant variability between samples. The epoxied aluminum tape was fairly stable during freezing, though significant variation was observable between samples. Epoxied connections experienced slight disruptions when placed in and removed from the freezer.

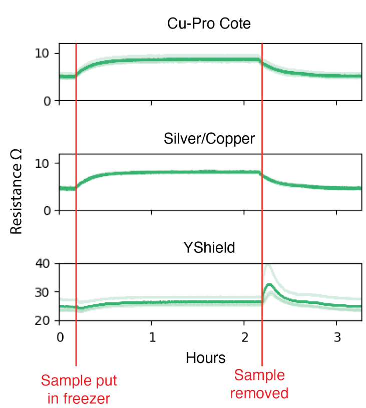


Fig. 10. **Conductive Paint**: Change in resistance due to freezing and thawing. Note that Y-axis values are different for YShield. Data for individual samples shown in light color, average shown in dark color. N=3 for each condition.

CuPro-Cote and Silver/Copper paints responded similarly to soldered tapes during freezing, Figure 10. Their resistance gradually increased during cooling, maintained a steady value when the freezer temperature was reached and returned to their initial resistance as they warmed back up to room temperature. The resistance of YShield experienced a sharp increase when the sample removed from the freezer and then a gradual decrease as it thawed.

No samples seemed to be harmed by this single freeze/thaw cycle. The resistances for all samples eventually returned to values that were indistinguishable from their initial resistances. We examine the behavior of materials and connections exposed to real-world repeated freeze/thaw cycles in Section 6.

5.3 Water Immersion

We are also interested in understanding how materials react to water. To investigate this characteristic, we submerged samples in water for 10 minutes and then removed them and allowed them to air dry, recording resistance changes during this process. For this test, when we submerged multiple samples simultaneously, we were unable to get meaningful readings; because water is electrically conductive, when multiple samples are submerged, measurements from different samples are not isolated. Due to this limitations, we used a single sample for each material. Because of the more limited data, results should be interpreted with caution.

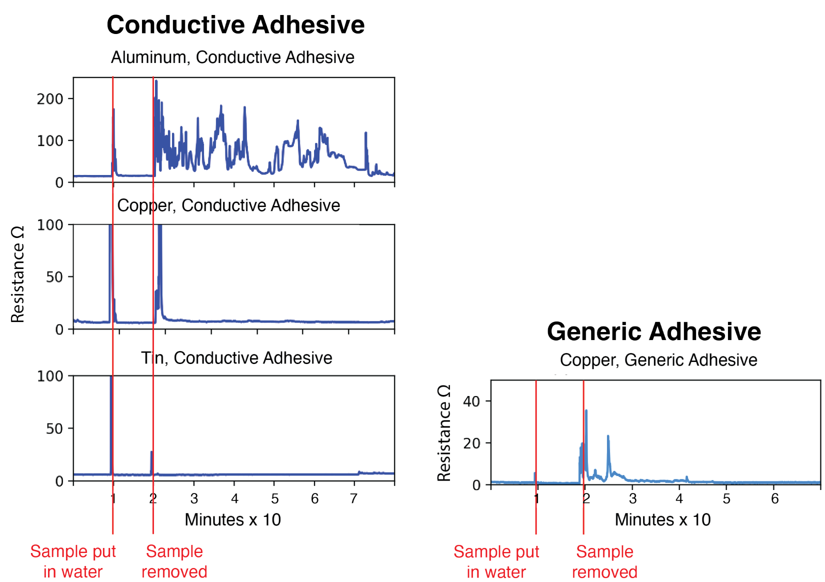


Fig. 11. **Conductive Tape**: Change in resistance due to water immersion. Note that Y-axis values are different for different materials. N=1 for each condition. No changes were observed for tapes that were soldered or connected via conductive epoxy.

Figure 11 shows the results of water immersion tests for tapes. Soldered and epoxied tapes exhibited no measurable change in conductivity during these tests, so those samples are not included in the Figure. The conductivity of connections made with conductive adhesive for Tin and Copper tapes are disrupted when they are placed in and removed for the water, as they are physically disturbed. Aluminum tape with conductive adhesive exhibits instability after being removed from the water, as does the sample of copper tape with generic adhesive.

The resistance of the latter material returned to its initial resistance after approximately 20 minutes, while the aluminum tape remained unstable for the remainder of the test period.

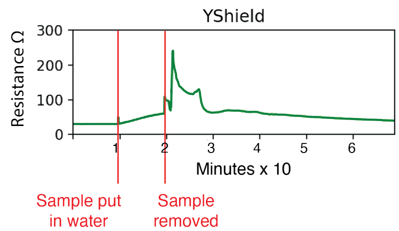


Fig. 12. **Conductive Paint**: Change in resistance due to water immersion. N=1. No changes were observed for CuPro-Cote or Silver/Copper paints.

CuPro-Cote and Silver/Copper paints exhibited no measurable changes for this test, but the behavior of YShield, which is shown in 12 is striking. The resistance of this material gradually increases while it is immersed in the water. When it is removed, the resistance increases dramatically and then gradually declines. It is noteworthy that this is similar to the behavior we observe for this material during freezing. (It is possible that YShield could be used as a low resolution temperature or moisture sensor.) After one hour the sample had not yet returned to its original value. After drying for several more hours, the resistance did eventually return to the original value.

Eventually, the resistance of all materials and connections except Aluminum tape, returned to their original values. It is possible that repeated water exposure would eventually degrade conductivity. Particularly in the case of materials like copper, which tarnish, repeated exposure may speed up degradation. However, we found no negative impacts from this short-term exposure.

Note that all of these samples were attached to substrates of primed Mural Paper. It is possible that this backing absorbs water in a specific way, thus impacting the results of these tests. We might record different results if the materials were attached to different substrates (ie: cement or plastic). Because we are interested in exploring how our materials behave in mural-relevant contexts, the results for Mural Paper remain useful for our intended application, however they should be referenced with caution as they may not represent the isolated behavior of the conductive materials. We learned more about water exposure in our outdoor tests, described in Section 6.

5.4 Two Years Later

To understand how different connection methods wear over time, we created a set of test strips and stored them for two years indoors on a flat shelf inside of a folder. We measured the conductivity of each sample at the beginning and end of this time period. The results of these tests are shown in Table 6. Each cell is color coded to indicate how much change occurred with green corresponding to little or no change and red corresponding to unacceptable levels of change. Note that, in contrast to the paint tests we presented in Section 4.1, these are tests of *connections between materials* rather than tests of a single material.

The most stable connections for tape are made through soldering. These connections experienced no measurable change in resistance over time. Conductive epoxy, which we used to connect Aluminum tape, since it cannot be soldered, degraded slightly. Tapes attached with conductive adhesive did not remain reliably connected over time. Generic adhesive was not a viable long-term connection mechanism either. For paint, connections made by painting CuPro-Cote and Silver/Copper over conductive tape were nearly as stable as soldered connections. In contrast, connections made by painting YShield were unstable.

	Solder	Tape: Conductive	Tape: Generic	Epoxy	Paint
Aluminum Tape		NC	NC	1.5 +/-1.9	
Copper Tape	0.0 +/-0.0	10.5 +/- 3.0	142 +/- 165		
Tin Tape	0.0 +/-0.0	NC			
CuPro-Cote Paint					0.1 +/- 0.1
Silver/Copper Paint					0.0 +/- 0.1
YShield Paint					1997 +/- 2616

Table 6. **Connections after two years**. Change in resistance after two years for connection test strips.Green cells indicate $< 1\Omega$ of change, yellow $< 5\Omega$, orange $< 20\Omega$ and red $> 20\Omega$. N=3 for each condition. NC = No Connection. (All connections made to bottom layer of copper tape.)

6 OUTDOOR DURABILITY

We further tested the durability of connections and materials by placing test boards in an exposed outdoor environment for extended periods of time. These tests were motivated by our interest in creating durable outdoor interactive murals. We also believe that these harsh conditions provide useful information for applications that may not need to withstand such extreme conditions. We conducted a series of long-term durability tests over the period of approximately one year, gradually improving our testing methodology and hardware during that time. Here, we report on our last set of tests that span a period of 100 days.

6.1 Test Set-up

Test boards were created from primed sheets of 300mm × 300mm (12" × 12") fiber board (MDF). Materials and connections were applied to the front of the board and testing hardware was placed on the back. Testing hardware was protected with a sheet of waterproof vinyl. We used the basic hardware configuration described in Section 5.1 and Appendix B, with 24 samples and one microcontroller on each board. The boards also contained BME680 temperature and humidity sensors. Resistance, temperature, and humidity readings were logged once per minute, for a sampling rate of 1440 readings per day.

We made a set of seven tests boards, each containing two basic connection configurations and three different protective covering configurations—no covering (bare), a white-paint covering and a black-paint covering. We wanted to determine if these coatings would improve or diminish the durability of our samples. Our choice to employ house paint as covering was motivated by the fact that in our murals, many of our conductive materials will be covered with traditional mural and/or house paint−see Figure 2 for an example. We chose to examine white and black paint to investigate how heat absorption, which varies by paint color, may impact material behavior.

It is important to note that there is a wide range of materials that are not considered here that could be (more) effective as protective coverings of conductive materials and connections. These include materials specifically designed to be waterproof, corrosion resistant, and UV stable. Our aim in these tests is to understand how

	Material	Connection 1	Connection 2
Tapes	Aluminum [1]	tape and epoxy	tape and screws
	Copper [2]	tape and epoxy	solder
	Tin [5]	tape and epoxy	solder
Paints	YShield [58]	paint only	paint and screws
	CuPro-Cote [37]	paint only	paint and screws
	Silver/Copper [21]	paint only	paint and screws

Table 7. Test configurations for long-term durability testing for each of our seven materials. Each connection listed above was tested without any protective covering (bare), with a covering of white paint and with a covering of black paint. See Figure 13.

interactive murals are likely to behave when constructed like traditional murals–that is, without applying additional weather-proofing materials to their surface.

Connection configurations are detailed in Table 7 and an example board, for Silver/Copper, is shown in Figure 13. The connection configurations for this board are: Connection 1 via paint and Connection 2 via paint and screws. Our short-term durability tests and preliminary long-term durability tests revealed the instability of tape-only connections, so these were not included in our outdoor tests.

Fig. 13. Test boards for long-term durability testing. Left: a board for Silver/Copper. Right: all boards installed outside. From left to right: CuPro-Cote, Silver/Copper, Copper Tape Generic Adhesive, Copper Tape Conductive Adhesive, Aluminum Tape Conductive Adhesive, Tin Tape Conductive Adhesive, and YShield.

For each material and connection combination we created three 6mm (1⁄4”) wide samples that spanned the length of the test board, Figure 13. Samples were connected at the left-hand side to strips of tin tape [5] via the specified connection method (conductive epoxy, solder, or paint). On the right-hand side, samples were connected to wires that led directly to the test hardware. For materials that could not be soldered, these wires were soldered to strips of tin tape which were then screwed down to the material.

The boards were attached to an exposed south-facing wall, Figure 13 right, and readings were acquired for 100 days. We recorded data from August 2nd to Septmeber 9th (38 days) at which points the boards removed and we conducted a preliminary data analysis. We rehung the boards on September 24th and collected data until November 24 (62 days).

6.2 Data Collection Problems and Data Filtering

We experienced some challenges in conducting our tests, primarily due to unanticipated power supply degradation– in which power supplies produced increasingly noisy output over the course of our tests. We believe this occurred because our standard low-cost 12V power supplies were left outside in the sun and were operating at close to their maximum wattage for the duration of the tests. This degradation resulted in noise being introduced into some of our sample data. For these readings, we identified high-frequency signal features that were common across all collected samples and subtracted these features to obtain a cleaner signal. We achieved this by subtracting the high-frequency features of one reference sample from all other samples. We used a second sample to remove noise from the reference sample in a similar fashion. Hardware errors–a broken SD card and a disconnected power supply–resulted in a complete loss of data from our Aluminum tape sample and limited data collection for our Tin tape sample.

6.3 Weather

Our test boards were exposed to a wide range of temperatures and several storms during the test period. The maximum temperature for our location during the period was 96°F (on August 7th) and the minimum temperature was 29°F (on November 22nd) [42]. The BME sensors mounted to our boards recorded a high temperature of 132°F and a low temperature of 27°F. Note that this sensor was mounted on the back of the boards, where electronics were covered vinyl, and does not accurately reflect the ambient air temperature or the temperature on the surface of the boards during the day. The high temperatures we recorded are much higher than the true ambient air temperature. However, the low temperatures recorded by our sensor, which occur at night, are accurate; we are able to compare these measurements to publicly available weather data [42]. The boards experienced freeze-thaw cycles on 6 of the 100 days, all towards the end of our testing window–November 13, 18, 19, 20, 22, and 23, (days 89, 94-96, and 98-99).

We received precipitation on 16 of the 100 days. All other days were either sunny or partly cloudy. Particularly significant storms occurred: August 11-14th (rain, days 9-13), August 26-September 4th (hail and rain, days 24-33), September 25-30th (rain, days 39-45) and November 23-24th (rain, days 99-100) [42].

Weather and freeze events are highlighted in all charts presented in this section.

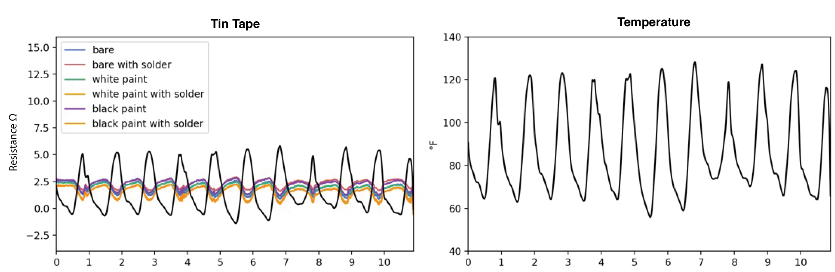


Fig. 14. Average hourly resistance for Tin Tape for 10 days. We observed a similar pattern for all materials.

6.4 Changes in Conductivity

6.4.1 Daily Changes. The resistances for all of our samples exhibited similar patterns of daily oscillation, with resistance decreasing slightly in the heat of the day and increasing slightly during the night. Figure 14 shows a plot of the resistances measured for Tin tape over the course of 10 days. A scaled plot of the temperature, shown in black, is overlayed on top of this graph for reference. A non-scaled plot of the temperature is also shown on the right side of the Figure. We observed this behavior for all materials, though for YShield, this pattern was less distinct, see Figure 18. Relative humidity follows a similar (inverse) pattern to temperature–decreasing during the day and increasing at night, so moisture rather than or in addition to temperature may be driving these shifts.

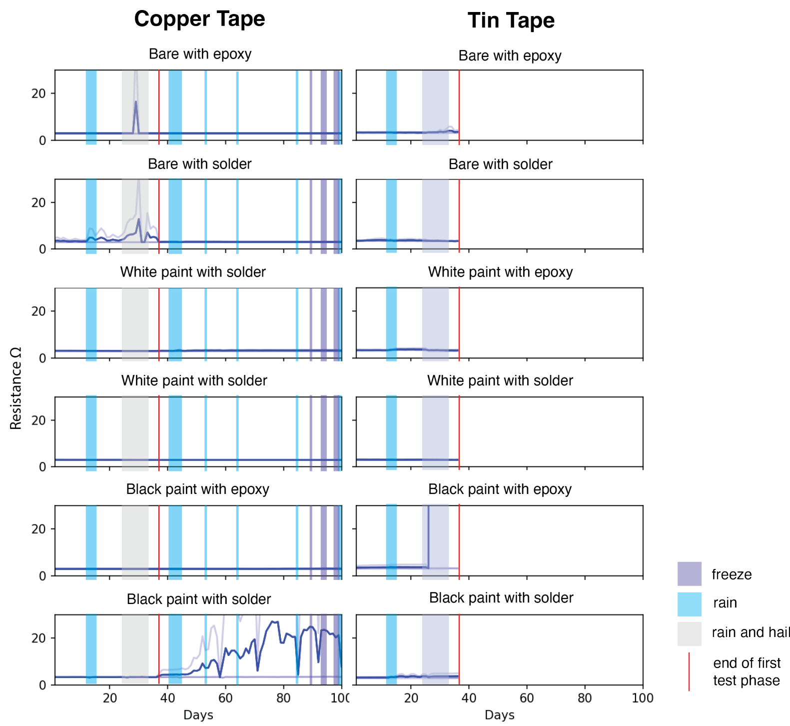


Fig. 15. **Conductive Tape**: Results from our outdoor exposure tests. Daily median resistance for Copper and Tin tape. Values for individual samples are plotted in light colors, averages for each condition are plotted in dark colors. N=3 for each condition.

6.4.2 Long-term Changes. Figure 15 shows graphs of the median daily resistance of conductive tape samples over the full 100 day period. Storms and freeze events are highlighted to help understand their impact on results.

Both Copper and Tin tape were impacted by the hail and rain storm (highlighted in grey) that began on day 24. One of the epoxied connection points for Tin tape was broken during this storm, second from bottom right in Figure 15. We believe the epoxied connection was broken loose when it was hit with hail. Two of the exposed copper tape connections were disturbed in this storm, one epoxied and one soldered, but recovered afterwards, see top left. The other noteworthy behavior was the degradation of one of the soldered copper tape connections that was covered with black paint. This change seemed to be triggered by the third rainstorm around day 40, see bottom left.

These disruptions, though they stand out in the graphs impact only 4 out of 48 samples. It is more important that almost all of the conductive tape samples–connected with solder and epoxy–remained stable over the course of the test. While we do not have complete time based data for Tin tape after day 38, we were able to manually measure the resistance of these samples at the end of the test period and verified that, except for the broken sample, they experienced no measurable degradation in conductivity.

Figure 16 shows the same data for CuPro-Cote and Silver/Copper paints. While these paints exhibited similar behavior in previous tests, in the outdoor durability tests, Silver/Copper clearly exhibits slower and less significant degradation than CuPro-Cote for all conditions. The degradation of CuPro-Cote seems driven by cumulative exposure more than precipitation or freeze/thaw events. (One CuPro-Cote sample seems to experience changes related to the first rainstorm, bottom left on Figure 16). Silver/Copper experiences fluctuations that do not seem to be related to precipitation, but it does does not exhibit the same amount of steady degradation as CuPro-Cote. The lack of change due to precipitation is unsurprising, given the lack of changes observed in our water immersion tests. Silver/Copper seems to be a better and more durable material for outdoor applications.

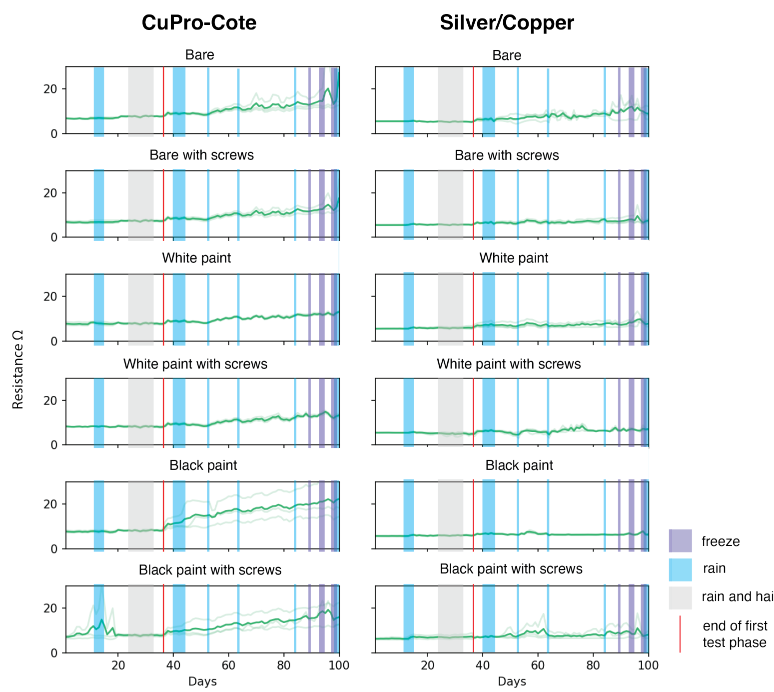


Fig. 16. **Conductive Paint**: Results from our outdoor exposure tests. Daily median resistance for CuPro-Cote and Silver/Copper. Values for individual samples are plotted in light colors, averages for each condition are plotted in dark colors. N=3 for each condition.

The results for YShield, which are shown in Figure 17 are qualitatively distinct from the other paints. YShield experiences more dramatic changes in conductivity, on the order of 100Ω throughout the test period. Some changes seem to be related to precipitation. The first and third storms seem to have had a significant impact on most samples, for example. This is not surprising, given the behavior we observed during our water immersion tests. Figure 18 shows average hourly temperatures plotted for the first 38 days (our first test period). In this data,

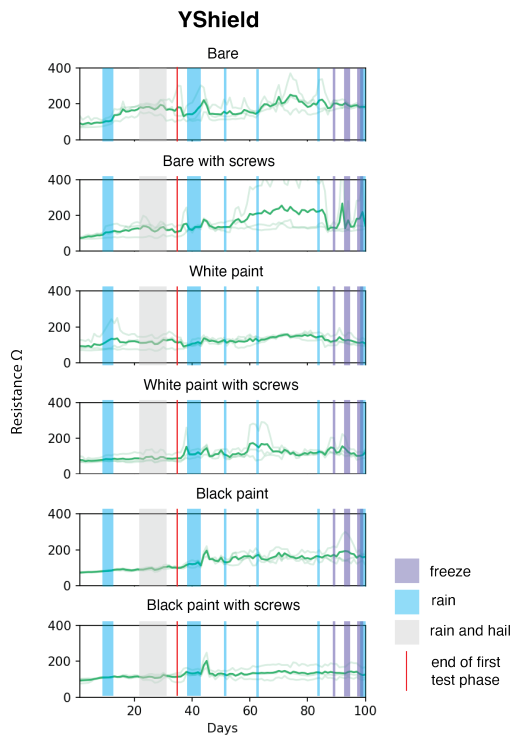


Fig. 17. **Conductive Paint**: Results from our outdoor exposure tests. Daily median resistance for YShield. Values for individual samples are plotted in light colors, averages for each condition are plotted in dark colors. N=3 for each condition.

some of the more complex behavior we observed in our water immersion tests are evident. Resistance increases immediately after a precipitation event, not during it. Also highlighted in this plot is the fact that there was a lull in precipitation in the middle of the rain and hail storm, which we did not highlight in the daily median graphs. During this time, the resistance in the YShield samples increased before falling again when precipitation resumed.

It seems from Figure 17 that precipitation is not the only driver of variation. Some large changes happen at other times. We could find no obvious weather events that correlated with, for example, the changes observable around day 60 for several samples. As with CuPro-Cote, there is a trend toward degradation over time, but YShield is more variable, both over time and across samples. Its behavior over time is too variable and unpredictable.

It is noteworthy that freeze/thaw cycles did not lead to significant changes in conductivity for any of our samples. However, it is possible that repeated freeze/thaw cycles occurring over longer time periods could impact samples. This topic warrants additional research, both "in the wild" and in the laboratory.

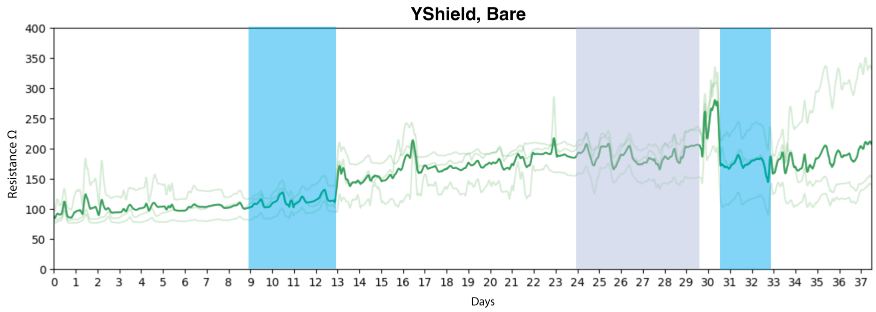


Fig. 18. Daily median resistance for YShield, bare condition. Values for individual samples are plotted in light colors, average plotted in dark color. N=3.

Table 8 shows the difference between the average starting and ending resistance for all of our samples. These values were calculated by averaging the 1440 readings taken on the first day of our test and comparing them to the 1440 readings taken on the last day of our test. Conditions that experienced relatively small overall changes ($< 10\Omega$) are shown in green, medium changes ($< 20 and < 50\Omega$) in yellow and orange, and large changes ($> 50\Omega$) in red. For Copper and Tin tape, both solder and epoxy were reliable connectors. For Silver/Copper and CuPro-Cote, comparing Table 6 to Table 8, makes it clear that exterior conditions result in degradation that does not occur to indoor samples. As we have already discussed, CuPro-Cote degrades more significantly than Silver/Copper under these conditions. If the trends we observed continued linearly, the CuPro-Cote traces would degrade at a rate of approximately $16\Omega/year$ in the best case, compared to $5\Omega/year$ for Silver/Copper traces. Adding screws to these connections improved them in almost all conditions. For the single condition that was not improved–Silver/Copper covered with black paint–the difference in the two conditions is not significant.

YShield exhibits the largest changes over time, with a best case trace degradation rate of $88\Omega/year$. Screws do not seem to impact YShield connections. These results align with the results of the two-year indoor durability tests we presented in Section 5.4, where we also saw significant degradation in YShield to tape connections.

Tape	**Connection 1: Epoxy**			**Connection 2: Solder**		
	Bare	White Paint	Black Paint	Bare	White Paint	Black Paint
Copper	0.5 +/- 3.3	0.1 +/- 0.2	0.5 +/- 3.1	0.2 +/- 3.0	0.7 +/- 5.3	5.7 +/- 7.3
Tin	2.9 +/- 4.6	0.1 +/- 0.1	NC	0.1 +/- 0.4	0.0 +/- 0.9	0.6 +/- 0.1
Paint	**Connection 1: Paint**			**Connection 2: Paint and Screws**		
Silver/Copper	3.9 +/- 1.0	2.2 +/- 0.6	1.0 +/- 0.9	2.2 +/- 0.9	1.4 +/- 0.7	1.5 +/- 0.6
CuPro-Cote	14.7 +/- 10.2	4.6 +/- 2.1	13.8 +/- 2.7	8.5 +/- 4.2	4.4 +/- 2.2	8.2 +/- 2.6
YShield	100.5+/- 6.8	24.2 +/- 9.7	88.2 +/- 12.6	123.9 +/- 45.2	28.6 +/- 8.9	30.3 +/- 9.1

Table 8. Average change in resistance from the beginning to the end of our outdoor tests. Materials experiencing $< 1\Omega$ of change are shown in dark green, $< 10\Omega$ in light green, $< 20\Omega$ in yellow, $< 50\Omega$ in orange and $> 50\Omega$ in red.

6.4.3 Impact of Coatings. It is difficult to draw conclusions about the impact of coatings on conductive tapes. Though coatings seem to be slightly helpful for most conditions, most differences all fall within the margin of error. For all paints, a coating seems to be somewhat helpful. For CuPro-Cote, white paint seems likely to be the best coating; black paint conditions do not perform significantly better than bare paint conditions. For YShield, white paint seems to offer the best protection, but black paint also prevents a significant amount of degradation.

6.4.4 Visual Evidence of Degradation. Our test boards also began to exhibit visual signs of degradation during the tests. The screws we used began to rust slightly and copper tape began to tarnish and turn green. We anticipate that copper tape kept outdoors will eventually oxidize and lose all of its conductivity. We also observed significant visual degradation for CuPro-Cote and slight degradation for Silver/Copper. Figure 19 shows before and after images for all of our materials.

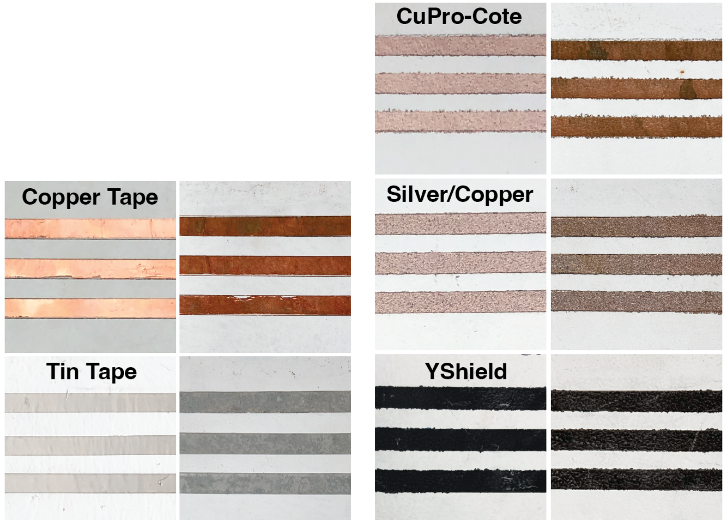


Fig. 19. Images showing materials before and after our outdoor durability tests. Conductive tapes are shown on the left and conductie paints on the right.

7 INTERACTIVE MURALS

In addition to conducting stand-alone material tests, we have completed two interactive mural projects. Our first outdoor mural was finished in July 2022. As of summer 2024, the mural exhibits no degradation in function. This 32×10 foot (10×3 m) mural, shown in Figures 20 and 2, was painted on an exterior wall of a building under a porch. The mural faces east and most of it is in direct sunlight in the mornings. During rain and snow storms, it is partially but not fully protected from the elements. The mural's circuitry is made from copper tape, LED light strips, and areas of Cu-Pro Cote that function as capacitive touch sensors.

Fig. 20. An outdoor interactive mural that is fully functional after one year. Circuitry, constructed with copper tape and CuPro-Cote is covered by mural paint.

The mural was collaboratively designed by the authors, a professional muralist, and a group of middle and high school students [13, 14]. Students designed the mural and did all of the painting, hardware installation, interaction design, and programming. We structured and guided the activity and provided support as needed, particularly during the hardware and software troubleshooting phases. The mural is controlled by five AdaFruit

Circuit Playgrounds. The interaction design is simple; LEDs are animated to highlight visual design elements in response to touch and other environmental sensor triggers.

There have been no visible changes in functionality since the mural was installed. All of the conductive materials are covered with mural paint, so we cannot measure their properties directly, but we have detected no loss of sensitivity in touch sensors and no visible dimming of LED lights.

Our second outdoor mural, shown in Figures 1, 3, and 21, which was also built collaboratively with our muralist collaborator and local youth, was installed in August 2023. This 44 × 10 foot (13.5 × 3 m) mural was painted on an exterior north-facing wall in a courtyard in a public museum. It receives no direct sunlight and is located under an overhanging roof. Like our first mural, it is partially but not fully protected from the elements. All of the conductive materials were left exposed since they are used as both decorative and functional elements–visible areas of conductive material function as capacitive touch sensors.

This mural creates shifting soundscapes in response to touch. It is controlled by six custom Printed Circuit Boards (PCBs). Each board contains two microcontrollers, one for capacitive sensing–six sensors per board–and one for real-time audio synthesis. The wall includes six speakers for sound output.

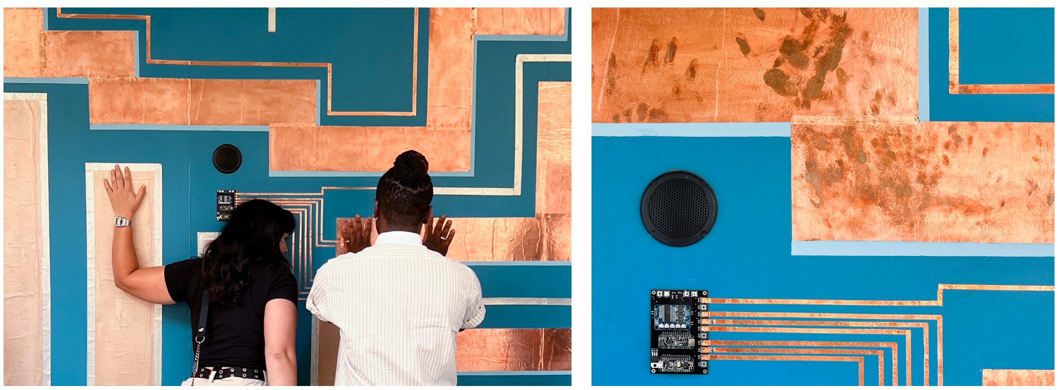


Fig. 21. Left: Museum-goers interacting with the mural. Right: a mural detail showing visible tarnishing on copper tape due to touch interactions. This image also shows a custom PCB and speaker

We have not detected any degradation in the conductivity of materials or connections due to outdoor exposure since its installation. However, we did encounter other durability issues. Because it is installed in a public art museum, this mural is subject to regular significant use. After two months, we observed considerable visual degradation of copper tape surfaces due to touch interactions, see Figure 21 right. It was clear that the salt, oil, and other substances on people's skin was beginning to tarnish copper surfaces. Though no change in material resistance was detectable, we decided to seal these surfaces for aesthetic and long-term durability purposes. In November 2023, we coated all copper areas with two coats of NovaColor 216 Exterior Acrylic Varnish, a clear UV-stable coating [43]. This action has prevented further tarnishing.

It is also worth noting that we had to conduct repairs on one area of circuitry that was damaged by users–an area of exposed conductive tape, that made connections between a PCB and capacitive sensors, was peeled away from the wall. In highly-trafficked settings like a museum, degradation due to user interaction is likely to be at least as significant a concern as degradation due to weather exposure. We expect that both of these murals will provide us with a deeper understanding of how conductive materials wear over time, due to weather related events, user interaction, and other unanticipated issues. (For example, we have recently noticed that spiders have been nesting in some of our PCBs.) We plan to continue to monitor and document what happens to both murals as they age.

8 DISCUSSION AND DESIGN RECOMMENDATIONS

Based on the tests we conducted, we have identified a collection of materials and connection methods that can be used to build robust interfaces that can withstand significant long term and outdoor exposure.

8.1 Materials

Material	**Overall Rating**	**Stability of Conductivity**	**Stability of Connections**	**Notes**
Copper tape	5	5	5	Excellent general purpose conductor.
Tin tape	5	5	5	Excellent general purpose conductor.
Aluminumm tape	2*	5	2	More testing required.
Silver/Copper paint	5	5	5	Excellent general purpose conductor.
Cu-Pro Cote paint	4	4	4	Good general purpose conductor.
Carbon paint	2	2	2	Unstable conductivity and connections.
Nickel paint	1	1	N/A	Very unstable conductivity

Table 9. A summary of our material findings. Materials ranked from 1 (not a viable conductive material, shown in red) to 5 (excellent general-purpose conductor, shown in green).

Table 9 provides a summary of our findings for the seven materials we investigated. The materials are ranked from 1 (not a viable conductive material, shown in red) to 5 (excellent general-purpose conductor, shown in green). The ranking indicates their suitability for building durable circuitry in wall-based interfaces. Our primary considerations, as noted in the table are the stability of the material's conductivity and the stability of the connections we are able to make with the material. Stability is considered cross both time and environmental conditions (as investigated in our tests).

Copper and tin tapes are excellent general purpose materials. We observed no changes in their conductivity in any of our tests. These two materials were the most conductive and most stable materials we considered. Both of these materials can be soldered. This means it is easy to make durable electrical connections between these materials and also between these materials and standard electrical components.

Aluminum tape maintains stable conductivity as a material, but it cannot be soldered, which makes it significantly harder to connect to other materials and electrical components like PCBs. It is possible to use conductive epoxy to make connections, but we observed these connections to be less stable than solder. Expoxied connections degraded significantly after two years, and were unstable in our freeze/thaw test. We were unable to collect usable data on aluminum tape connected via conductive epoxy in our outdoor testing. More research is warranted to make final recommendations regarding aluminum tape and conductive epoxy. However, it is clear that tin and copper tapes are better options for most applications.

Silver/Copper paint is an excellent general-purpose conductive paint and Cu-Pro Cote is a good one. Silver/Copper paint was the most conductive and most stable paint we considered. We detected no measurable change in the resistance of Silver/Copper or CuPro-Cote after two years indoors. Both materials did degrade in outdoor tests. Silver/Copper lost conductivity outdoors at the lowest rate we observed for paint. CuPro-Cote degraded significantly faster than Silver/Copper in outdoor conditions. Both paints maintained useful conductivity for the duration of all of our tests. Stable connections can be made by painting Silver/Copper or Cu-Pro Cote over conductive tape. This makes them easy to employ in combination with other materials, including solderable materials like copper and tin tape.

YShield is not a viable conductive material. YShield, the carbon-based paint, has poor conductivity compared to Silver/Copper and Cu-Pro Cote and very poor stability. This paint's conductivity was very sensitive to environmental factors, particularly water exposure. We believe that, likely because of this sensitivity, it was significantly more challenging to establish stable connections between YShield and other materials. Connections between YShield and conductive tape were nonfunctional after two years indoors and our outdoor samples experienced significant degradation along with significant variability. It is possible that YShield could have other applications in murals and other wall based interfaces. Our results indicate that it could potentially be used to build custom sensors. However, it should not be used as a conductive material in wall-based circuitry.

Similarly, *Nickel paint is not a viable conductor.* Its conductivity is poor compared to Silver/Copper and Cu-Pro Cote. Most improtantly, its conductivity degrades rapidly. This material lost all of its conductivity after two years indoors.

8.2 Connections

Table 10 provides a summary of our findings on connection methods. The methods are ranked from 1 (not a viable connection method) to 5 (excellent connection metod). Again, the ranking indicates each method's suitability for building durable circuitry in wall-based interfaces.

Soldering is the best connection method. Painting Silver/Copper or CuPro-Cote paint over conductive tape is also a robust and viable connection method. We do not recommend the use of conductive epoxy. Expoxy is only necessary when using a non-solderable material like aluminum. Further study of this connection method is warranted.

It is worth highlighting that *tape-only connections, including via tapes with conductive adhesive, do not provide durable electrical connections.* All tape-only connections were nonfunctional after two years indoors. Moreover, all of these connections were sensitive to moisture exposure and freeze/thaw cycles.

	Solder	Tape: Conductive	Tape: Generic	Epoxy	Paint
Copper Tape	5	1	1	5	
Tin Tape	5	1		4	
Aluminum Tape		1		2*	
Silver/Copper Paint					5
CuPro-Cote Paint					4
YShield Paint					2

Table 10. A summary of our connection findings. Connection methods are ranked from 1 (not a viable conduction method, shown in red) to 5 (excellent connection method, shown in green).

9 CONCLUSION

We conducted a range of tests to determine the durability of conductive tapes and paints under different circumstances. We have explored how materials and connections wear when subject to freezing, water immersion, and extended indoor and outdoor exposure. We have exposed problematic materials and methods. Taped connections (made with conductive or generic adhesives) are highly unreliable. Nickel paint, which has been used in previous interfaces [59], corrodes rapidly.

We have also identified suitable materials and connection techniques. Silver/Copper paint, Copper tape, and Tin tape all have low resistance and remained quite stable across all of our tests. CuPro-Cote remained stable for all but the outdoor durability tests. We believe that these four materials can be used successfully in interactive murals as well as other interfaces that require long-term durability.

Outside of the concrete utility of the tests we have described, we see our investigations as contributing to an important area of HCI and Ubiquitous Computing that does not receive enough attention–the development and testing of real world systems that people interact with outside of laboratory settings for extended periods of time [35]. Most HCI and Ubicomp research is focused on developing and demonstrating novel ideas quickly. This kind of work makes for clear and compelling research papers. When building larger scale real-world systems, a significant amount of the work, including the research, is less immediately exciting. But, it is equally important. To better understand how *real people* and real communities adopt and use *real systems*, we have to build foundations that support research beyond prototypes. The work we have presented strives to build this kind of foundation.

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A CONDUCTIVITY AFTER 2 YEARS: ADDITIONAL INFORMATION

The following table shows additional information on our two-year conductivity tests.

Tape	**Solder**		**Conductive Epoxy**		**Conductive Adhesive**		**Generic Adhesive**	
	initial (Ω)	change (Ω)	initial	change	initial	change	initial	change
Aluminum			1.8 +/-.7	1.5 +/-1.9	2.9 +/-1.1	NC	NC	NC
Copper	0.0 +/-0.0	0.0 +/-0.0			1.8 +/-0.7	10.5 +/- 3.0	2.0 +/- 0.5	142 +/- 165
Tin	0.0 +/-0.0	0.0 +/-0.0			0.3 +/-0.6	NC		
Paint	**Paint (over tape)**							
CuPro-Cote	0.5 +/- 0.1	0.1 +/- 0.1						
Silver/Copper	0.5 +/- 0.1	0.0 +/- 0.1						
YShield	26.3 +/- 6.7	1997 +/- 2616						

Table 11. Change in resistance after two years for connection test strips. Green cells indicate $< 1\Omega$ of change, yellow $< 5\Omega$, orange $< 20\Omega$ and red $> 20\Omega$. N=3 for each condition. NC = No Connection.

B TESTING HARDWARE: ADDITIONAL IINFORMATION

This appendix provides additional information about the testing hardware we employed in our indoor and outdoor durability tests. We want to track the change in materials' conductivity over time. The materials we are testing have low resistances and many of the resistance changes we want to detect are small, on the order of 1-10 ohms. A naive voltage divider circuit to test these kinds of resistance changes would draw a significant amount of power, essentially creating a short circuit between power and ground.

Compounding this problem, we are interested in testing many different material samples at the same time. Adding several voltage dividers to a circuit in parallel worsens the issue. The resistance between power and ground (R_t) for one of our voltage dividers—assuming the material we are testing has negligible initial resistance—is 600 Ω, Figure 22, (a). If we add voltage dividers to our circuit, the resistance R_t, given by Kirchoff's laws, is $600/n$, where n is the number of voltage dividers, Figure 22 (b). This makes collecting data from multiples material samples problematic. For $n = 3$, $R_t = 200$ Ω; for $n = 24$, $R_t = 25$ Ω. Moreover, changes in the resistance of one material sample will result in changes to our measurements for all other materials. To solve these issues, we add a multiplexer between VCC and our pullup resistors. This isolates all of our sensors and ensures that Rt is always ≥ 600 Ω, Figure 22 (c).

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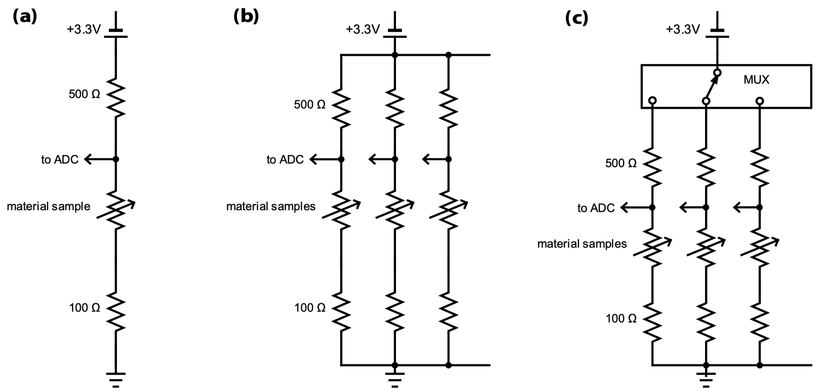

Fig. 22. our basic voltage divider setup, $R_t \geq 600\Omega$. (b): voltage dividers in parallel. For $n = 3$, $R_t \geq 200\Omega$; for $n = 24$, $R_t \geq 25\Omega$. (c): Our final testing setup includes voltage dividers with a multiplexer to connect VCC. $R_t \geq 600\Omega$

Moreover, changes in the resistance of one material sample will result in changes to our measurements for all other materials. To solve these issues, we add a multiplexer between VCC and our pullup resistors. This isolates all of our sensors and ensures that R_t is always >= 600Ω,