Supplementary Information for

"Dip-and-read" paper-based analytical devices using distance-based detection with color screening

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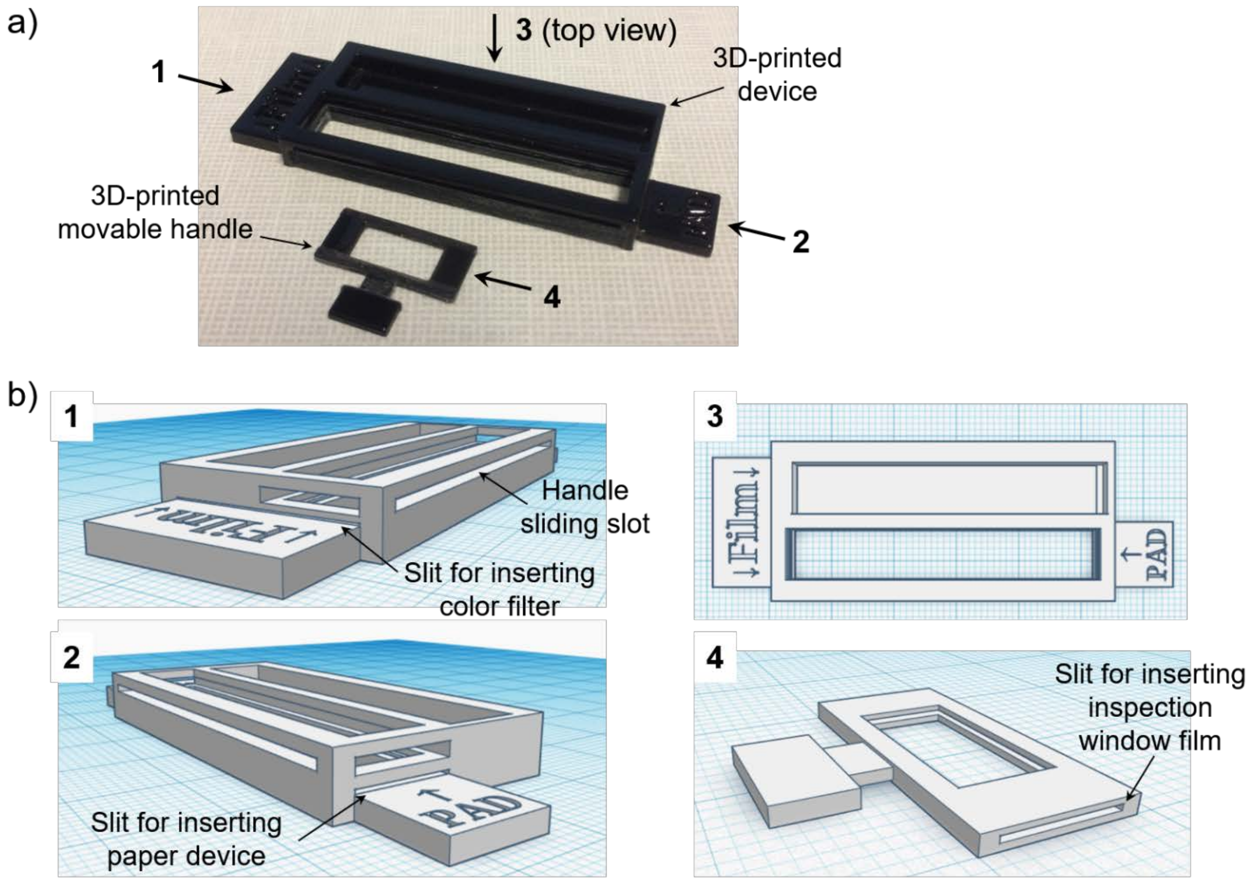

Figure S1. Design of the 3D-printed device for distance-based quantification on a paper device by color screening: a) actual photograph of the 3D-printed device and movable handle part for the inspection window sliding; b) screenshots of the Tinkercad CAD software showing the detailed structure of the 3D-printed device and handle part from 4 viewpoints as indicated in part a).

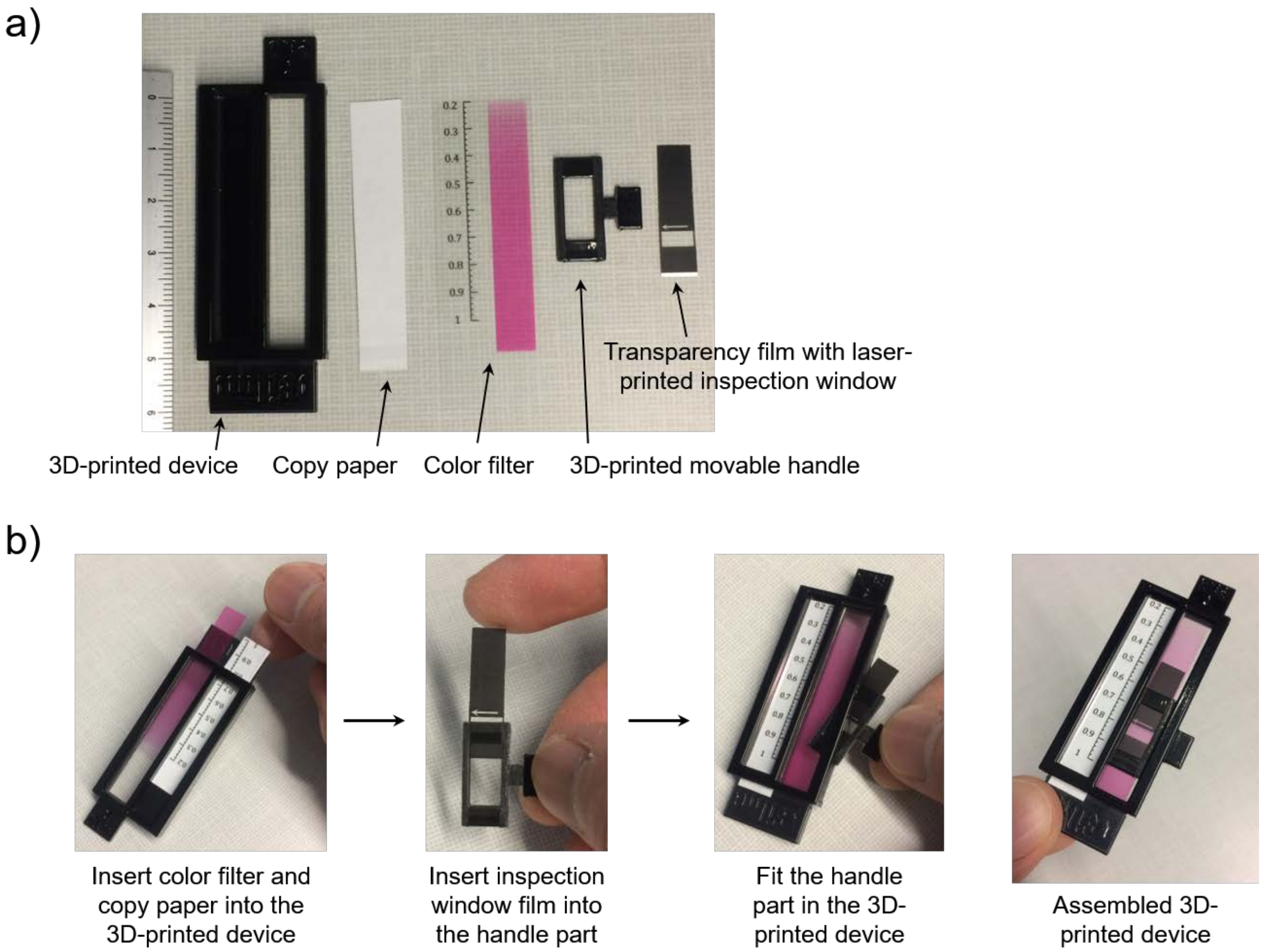

Figure S2. a) Device components for the distance-based assay by the color screening approach; b) assembly process of the device components.

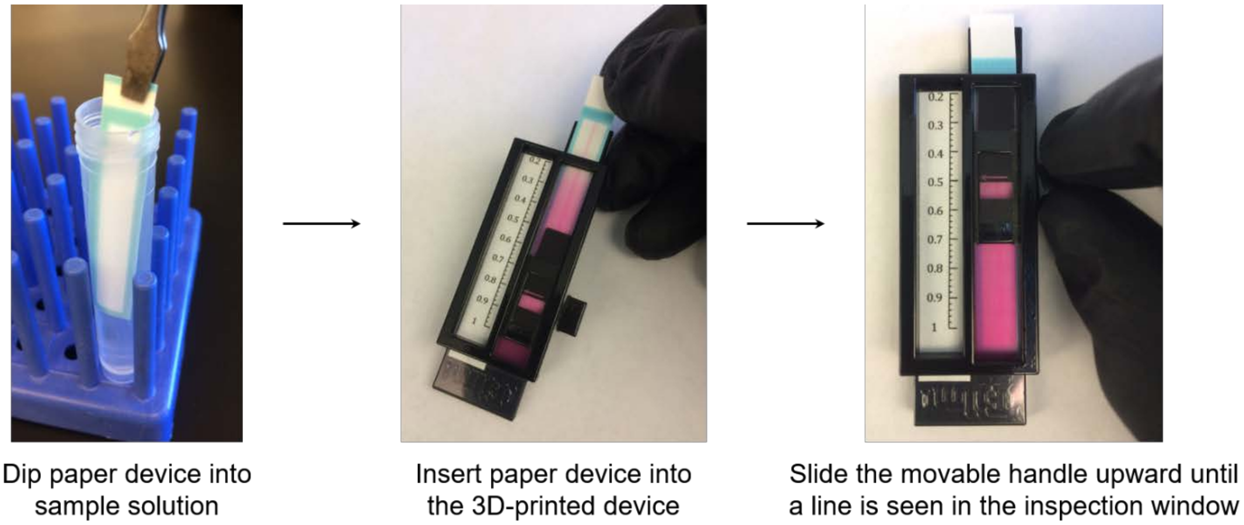

Figure S3. Operational procedure of the distance-based assay by the color screening approach.

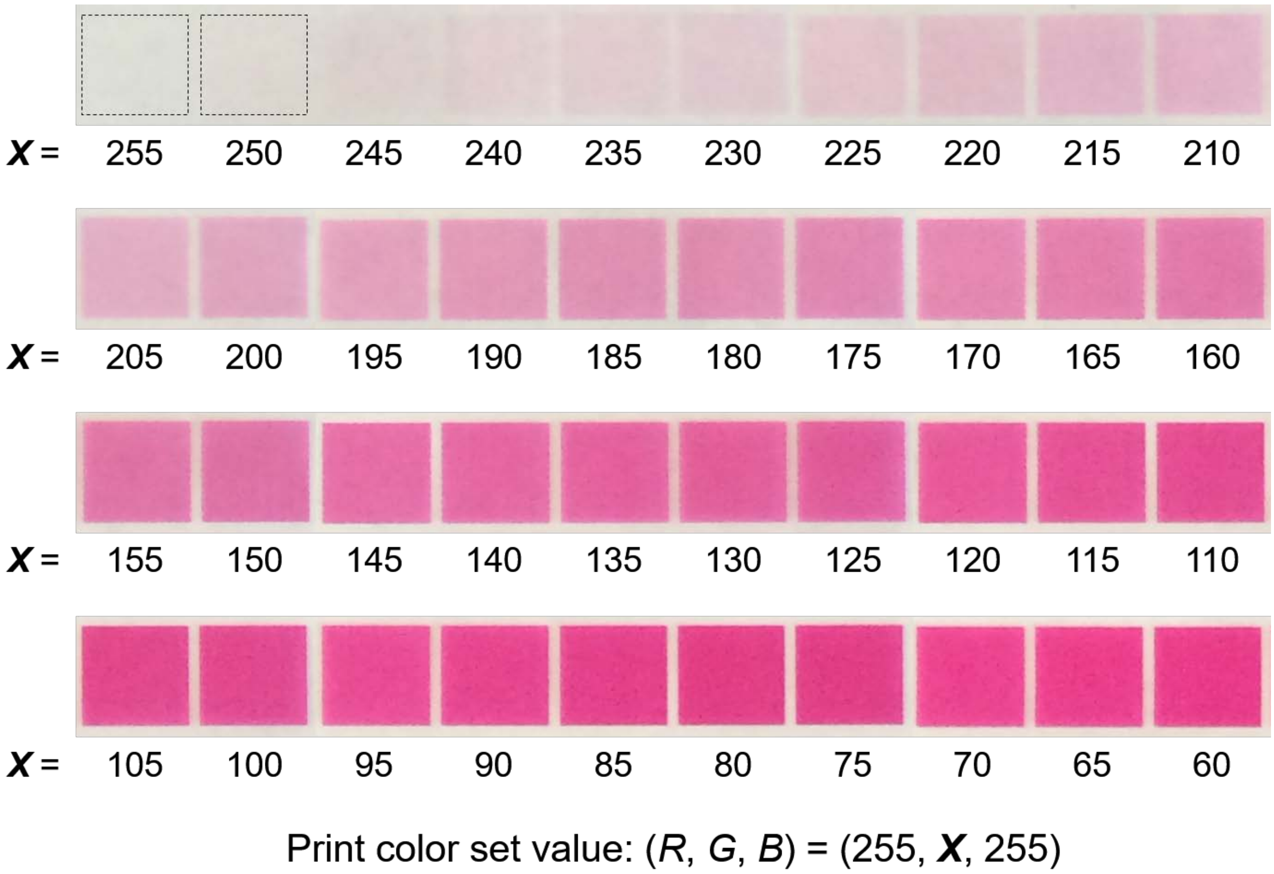

Figure S4. Magenta filtering color on a transparency film printed with various intensities.

Detailed characterization of the color gradient printed on the color filter

In this section, the continuous color gradient printed on the color filter is quantitatively analyzed, and agreement with optimized color intensities in Figure 3b of the main text is described.

On the basis of optimized printer set color values, the color gradient profile shown in Figure S5a was created on PowerPoint software. Figure S5b represents the actual photograph of the printed color gradient on a transparency film. The black line in Figure S5c represents the plot profile of magenta color intensity of the color filter at the locations shown in Figure S5b. Since the ImageJ software used in this work does not allow direct measurement of magenta color intensity values, this parameter was quantified from inverted green channel images, based on the fact that magenta and green colors are complementary to each other. Magenta color intensity values were extracted from the scanned image of the color filter by: 1) splitting the color image into R (red), G (green), B (blue) channel images (click “Image” → “Color” → “Split channels”); 2) obtaining an inverted image in green channel showing the magenta color intensity in black-and-white mode (select the green channel image and click “Edit” → “Invert”); 3) analyzing longitudinal color intensity (select “Straight” region of interest and click “Analyze” → “Plot profile”). Figure S5c shows that the filtering magenta color gets more intense in a continuous manner with increasing scale mark position in Figure S5b.

On the other hand, red circles in Figure S5c represent “targeted” magenta color intensity values at each position of the color filter. To obtain these data, the optimized color intensity value settings in Figure 3b of the main text were converted to a corresponding magenta color intensity values by using the “sample” color filter in Figure S4. In this conversion step, the relationship between the pre-set print color value and the printed magenta color intensity (Figure 5d) has been used. Good agreement between the data of black line and red circles in Figure 5c demonstrates that the filtering colors optimized in Figure 3b is successfully transferred to the color gradient in Figure 3c.

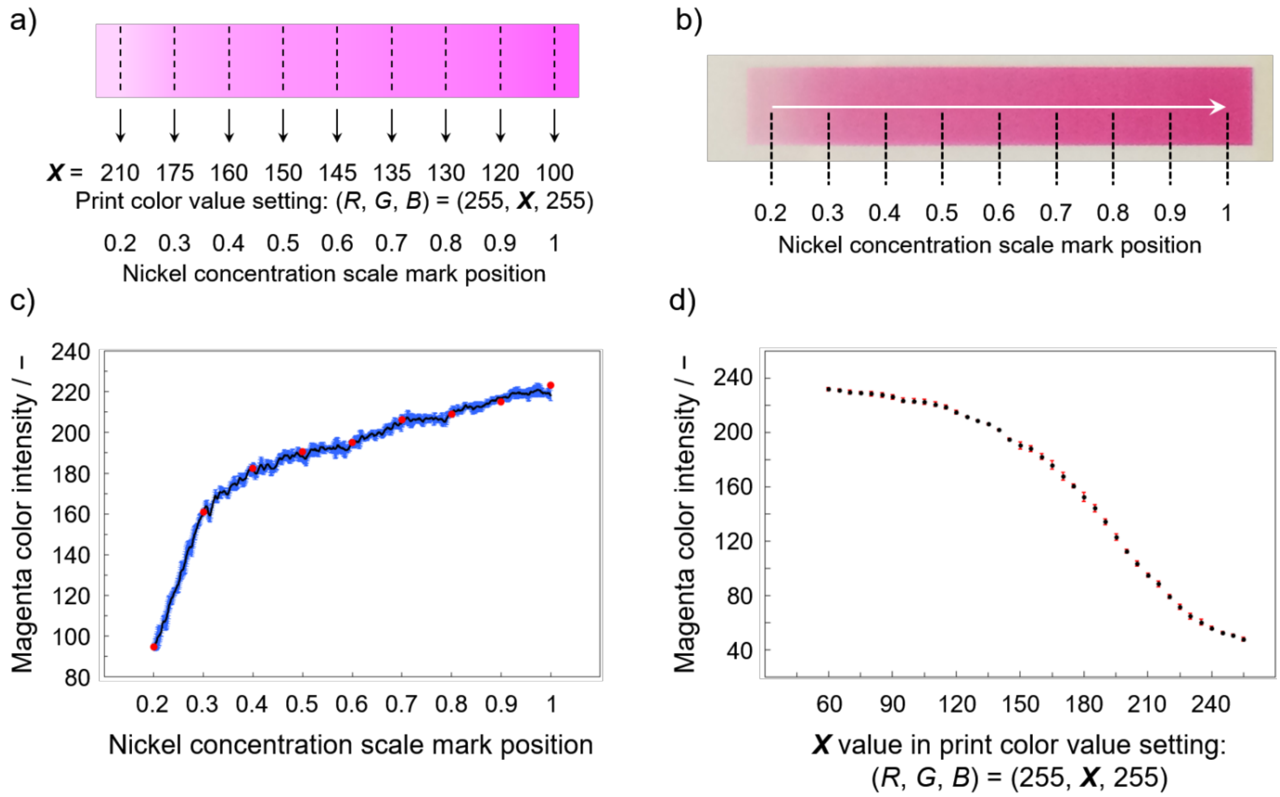

Figure S5. a) Printing graphic design of the filtering color and print color value settings on the PowerPoint software; b) actual photograph of the color filter and concentration scale marks printed on a transparency film; c) detailed profile of magenta color intensity of the color filter. The "Nickel concentration scale mark position" of the horizontal axis corresponds to the longitudinal position on the color filter as shown in part b). The black line and blue error bars reflect the average and standard deviations of the results obtained from 6 independent color filters, respectively. The red circles represent the "targeted" color intensity values based on the optimization result shown in Figure 3b of the main text; d) correlation between the print G (green) color value setting and resulting magenta color intensity printed on a transparency film. The black markers and red error bars reflect the average and standard deviations of 4 independent measurements.

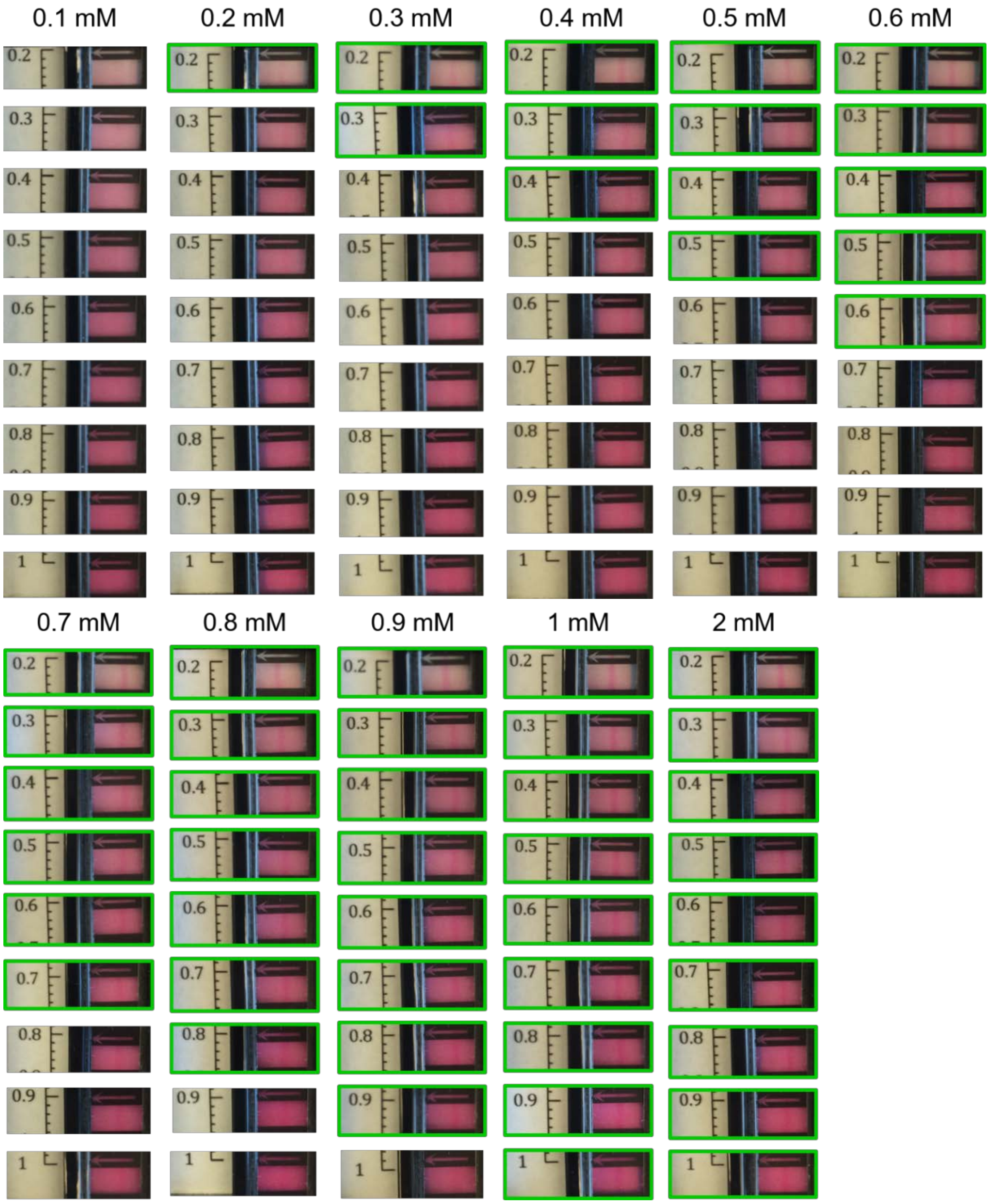

Figure S6. Photographs of the inspection window in the detection of various concentrations of Ni. The image boxes highlighted by the green outline show the visible state of the vertical line inside the inspection window. Note that the light blue lines seen to the left of the windows are shadows of a part of the 3D-printed device.

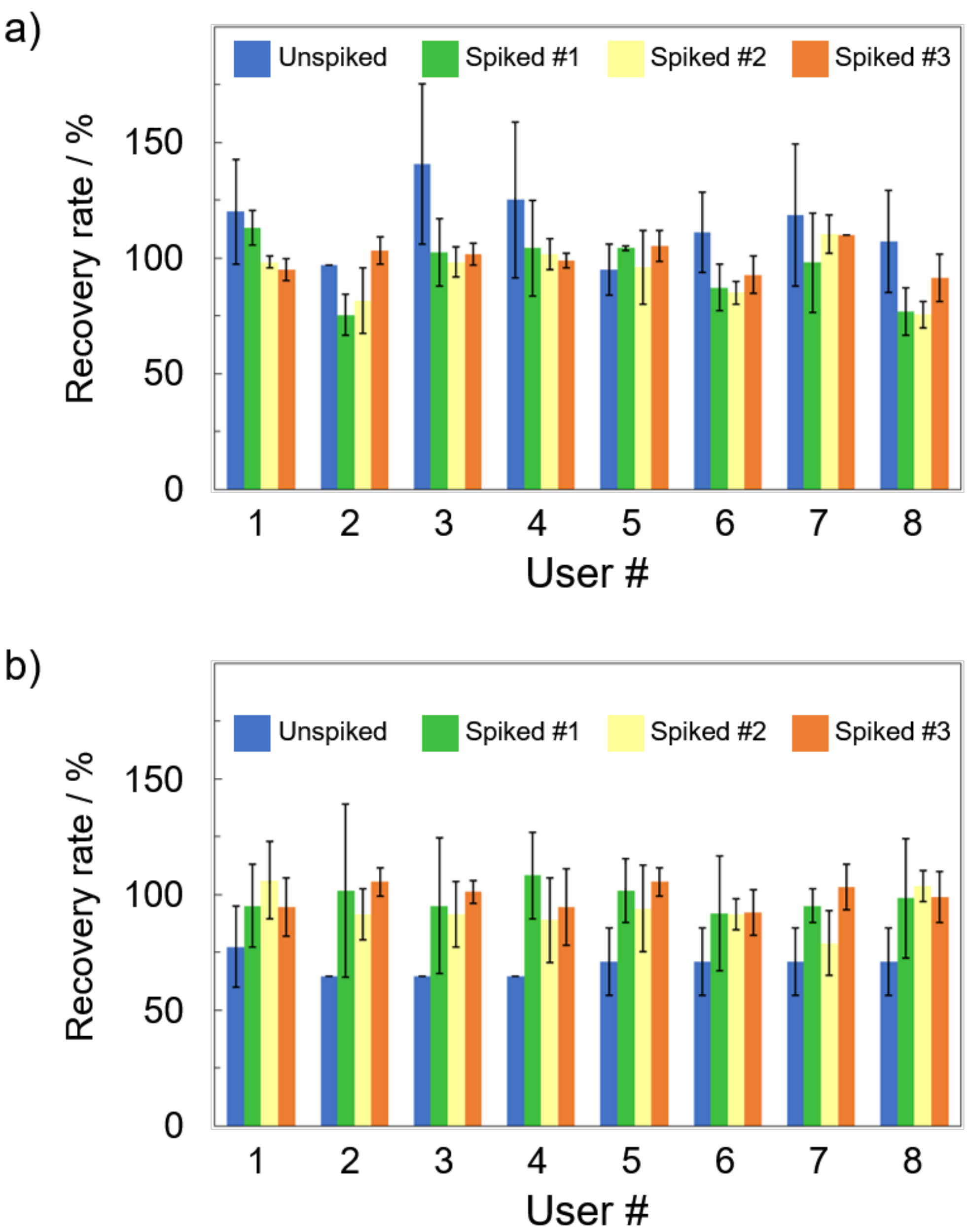

Figure S7. Bar graphs showing the recovery rate (%) of the user test-based quantification of Ni digested from a welding fume. The data reflect 5 independent measurements by a) the proposed distance-based method and b) naked eye-based color intensity comparison. The results correspond to those in Table 1 of the main text.

Table S1. Certified content of metals in the SSWF-1 reference material.[1]

Metal	**Certified value / % m/m** [a]	**Uncertainty**
Nickel	3.7	± 0.2
Chromium	8.4	± 0.4
Manganese	22.9	± 0.5
Iron	29.8	± 0.9

[a] The certified value has been determined by means of inductively coupled plasma-atomic emission spectrometry (ICP-AES).

Table S2. Cost estimation for the developed paper-based analytical device (PAD).

Material cost

Material	Market price per quantity	Quantity per PAD	Cost per PAD
DMG	\$120/500 g	14 µL (20 mM)	\$0.00000778
Tris	\$185/500 g	14 µL (10 mM)	\$0.00000625
Ammonium acetate	\$260/2.5 kg	70 µL (1.2 M)	\$0.000674
Sodium fluoride	\$132/500 g	70 µL (0.3 M)	\$0.000232
Filter paper	\$468.64/46 × 57 cm^2 × 100 sheets	0.6 × 5 cm^2	\$0.00536
Laminate film	\$43/200 letter-sized sheets	(4 PADs/letter size)	\$0.00448
Total			\$0.0108

Printing cost

Wax printer (ColorQube 8870): \$0.0000341

Inkjet printer (Canon PIXMA MG2525): \$0.000167

*Based on the printer lifetimes of 120,000 pages (wax printer) and 5,000 pages (inkjet printer), 48 PADs per letter page.

Total material cost of single PAD = \$0.0108 + \$0.0000341 + \$0.000167 = **\$0.011**

Reference

[1] Health & Safety Laboratory, Certificate of analysis, HSL SSWF-1 Reference Material, https://www.hsl.gov.uk/media/231813/hsl%20sswf-1%20certification%20sheet%20v1%20final.pdf (accessed March 9, 2018).