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Da Vinci's Mona Lisa entering the next dimension

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Abstract

For several of Leonardo da Vinci's paintings, such as *The Virgin and Child with St. Anne* or the *Mona Lisa*, there exist copies produced by his own studio. In case of the Mona Lisa a quite exceptional, re-discovered studio copy was presented to the public in 2012 by the Prado Museum in Madrid. Not only does it mirror its famous counterpart superficially, it also features the very same corrections to the lower layers, which indicates that da Vinci and the "copyist" must have elaborated their panels simultaneously. On the basis of subjective (*N*=32 participants estimated painter-model constellations) as well as objective data (analysis of trajectories between landmarks of both paintings), we revealed that both versions differ slightly in perspective. We reconstructed the original studio setting and found evidence that the disparity between both paintings mimics human binocular disparity. This points to the possibility that the two *Giocondas* together might represent the first stereoscopic image in world history.

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Only some years after Leonardo's death, Renaissance artist and biographer Vasari (1568/2008) praised the *Mona Lisa* as a portrait "painted in a way that would cause every brave artist to tremble and fear" (p. 294), and it should retain the status of a chef d'oeuvre throughout the succeeding centuries. The spectacular robbery in 1911 and the painting's return to the Louvre in 1913 inflamed *Mona Lisa*'s popularity. Later on it inspired works of art movements such as Dada (Duchamp) or pop art (Warhol), and finally became an icon of popular culture (remember Nat King Cole singing "Mona Lisa").

Mona Lisa now and then

In the Renaissance days, the *Mona Lisa* (painted 1503-1506 and later, Zöllner and Nathan 2011) looked quite different from what she looks like today. In all probability, the coloration was significantly fresher, and, concerning the background, composed of blue hues as indicated by small areas in the upper part of the painting that have not darkened over the years (Zöllner and Nathan 2011). These assumptions about the original appearance of the painting are further supported by efforts to virtually remove the yellowed varnish that could identify lapis lazuli (an intense blue) in the painted sky (Elias and Cotte 2008).

Though ageing took its toll, the *Mona Lisa* still gives a fine example of Leonardo's artistic mastery and his often innovative practice. He executed the painting in an extraordinarily subtle manner. Advancing the *glaze technique* known from Flemish painters of the 15th century such as van Eyck and van der Weyden (Elias and Cotte 2008), he applied the pigment in multiple ultra-thin, super-imposed layers, in order to shape *Mona Lisa*'s face, for instance. This sophisticated use of the so-called *sfumato* created particularly "soft transitions from light to shade" and a "luminous and tangible" impression (Ruhemann 1961, pp 233). Concerning the subject, Leonardo further attained an innovative implementation that

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expanded the (bust) portrait tradition prevalent in Italy back then (e.g. by choosing a larger format and by presenting the sitter closer to the observer than usual) (Zöllner and Nathan 2011). The resulting novel character made the *Mona Lisa* a prototype influencing further developments of the portrait genre in general—it was indeed "stilbildend" (German technical term for "style-forming").

The (re-discovered) Prado version

In 2012, the Museo del Prado in Madrid presented a restored copy of the *Mona Lisa* that went unheeded until then as its background had been obscured by black overpaint for a long time (since 1750, at the earliest, Prado Museum 2012). When the conservators of the museum removed the black colour, they made an astounding discovery: They found a landscape that was pretty much the same as the one in the famous Louvre match, which can be observed very well when inspecting the restored Prado copy and the virtually unvarnished Louvre version (see Elias and Cotte 2008, Figure 1 right panel) next to each other. The landscape, however, is not the only feature that makes the Prado version stand out against the various other copies of the Mona Lisa (see Table 1, for a selection of well-known copies).

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Table 1. Selection of well-known copies of the *Mona Lisa* (in alphabetical order).

Copy	Exhibited/ owned by…	Assumed time of origin
Isleworth Mona Lisa	anonymous owners; presented by the Mona Lisa Foundation, Zurich/ Switzerland	around 1500 (?)
Prado Mona Lisa (La Gioconda Velata)	Museo del Prado, Madrid/ Spain	ca. 1503
Reynolds Mona	private collection (exhibition at Dulwich	early 17th century

Lisa	Picture Gallery, London/ Great Britain in 2006/ 2007)	
Vernon Mona Lisa	unknown (sold by Sotheby's New York in 1995)	16th century
Walter's Art Museum Mona Lisa	Walter's Art Museum, Baltimore/ Maryland USA	late 16th/ early 17th century

For the face area of the two Mona Lisa versions, a high congruency in shape aspects has already been documented by Carbon (2013) who used a bi-dimensional regression analysis approach (BiDimRegression *R* algorithm) to compare the two paintings (Euclidean solution: $R^2 = .998$, with $F_{2,68} = 20{,}089.2$, $p < .0001$). Multiple analyses performed by the Museo del Prado further revealed that the close resemblance of Prado and Louvre version is not limited to the superficial appearance (Prado Museum 2012). By comparison of the respective infra-red reflectography results something interesting became visible: The genesis of the Louvre version is almost completely repeated in the Prado version, in fact from preparatory drawing to upper paint layers; even specific corrections (e.g. of the position of the fingers) are present in the drawings of both portraits. This suggests that the person who painted the Prado version might actually have observed the complete creation of the original portrait "live". Leonardo and the copyist might even have stood there together in the studio, painting simultaneously.

Studio setting: New insights due to the Prado version

The Prado version opens the opportunity to get insights into Leonardo's studio at the time he created his famous *Mona Lisa*. If Leonardo and the second painter really worked simultaneously, standing next to each other, they would have had at least slightly different

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perspectives on the sitter, which should also be reflected in their paintings. Consequently, we should be able to reconstruct the spatial arrangement of the artists and their model from the perspectival difference perceptible when having both paintings at hand. In order to do so, we asked N = 32 participants (26 female; age M = 21.3 years, SD = 2.7) to closely inspect the Louvre and the Prado version of the *Mona Lisa* and to estimate the painter's position (in terms of distance and direction) relative to the model for each of them. The averaged subjective assessments of the paint scenes were then compared to each other, which yielded a tiny but significant difference between the spatial painter-sitter configurations of the two paintings. The difference in direction was $\alpha = 1.9°$ (deviations from the perpendicular: 2.1° for the Louvre vs. 4.0° for the Prado version, $p = .0006$, $d = .694$; note: the larger the angle the more rightwards the painter's position as seen from the depicted person). The difference in distance was 1.0 m (distance from the sitter: 3.1 m for the Louvre vs. 2.1 m for the Prado version, $p = .0012$, $d = .661$). Figure 1 visualizes the perspectival difference in question as calculated by means of linear trajectories (1C & D) between unambiguously corresponding landmarks that we set in the Louvre (1A) and the Prado version (1B), respectively (the landmarks were organized in nine different categories; e.g. the tip of Mona Lisa's nose in both versions was a landmark belonging to the "face" category). Figure 2 schematically depicts the potential original setting in Leonardo's studio as reconstructed from the position estimates our participants had made on basis of the paintings.

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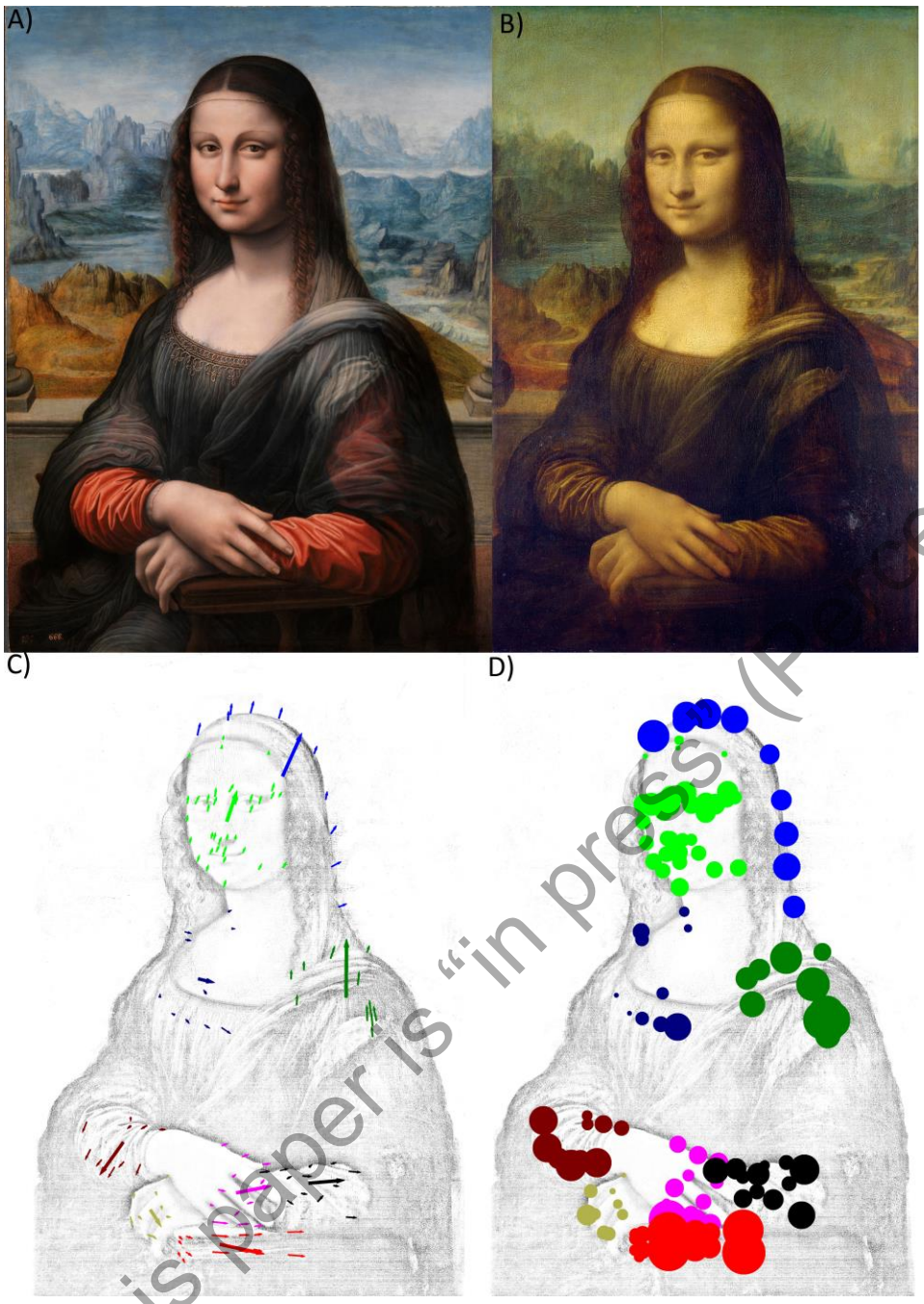

Figure 1. Two times Lisa: The famous Mona Lisa exhibited in the Louvre/Paris (B) and her sister painting in the Prado/Madrid (A). The perspectival change between them is visualized by linear trajectories (C) between the corresponding landmarks set in the Louvre and the Prado version, respectively, with the Louvre coordinates taken as starting points. The *N*=124 trajectories are organized in nine categories: face (*n*=36; neon green), hair (*n*=10; blue), body left (Lisa's upper left body side; *n*=11; dark green), body right (*n*=10; dark blue), left arm (*n*=12; black), right arm (*n*=10; brown), left hand (*n*=9; light green), right hand (*n*=12; pink), chair (*n*=14; red). Thick arrows indicate the categories' average trajectories. The changed perspective can most easily be observed in the picture elements showing Mona Lisa's hands and her head. The length of trajectories is additionally visualized as diameters of the circles in (D).

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A special double: Made for a specific purpose?

It is well established that producing copies of the master's works was a common practice in Leonardo's studio. For *The Virgin and Child with St. Anne*, for instance, several precise studio copies of high artistic quality exist (Nathan 1992). So it is not at all surprising to find at least one minute copy of the *Mona Lisa* as well. In case of the Prado double, however, there is one particularly striking detail not uncovered until now that might distinguish this copy from other copies usually made by Leonardo's studio: As mentioned already, there is a slight perspectival difference between Louvre and Prado version. Importantly, this difference does not seem to be of random but of systematic nature. As Figure 1C illustrates, the lower image area (i.e. left and right hand, left arm, chair, but also the right body) shows a pattern of consistent horizontal disparities. In this respect, the pattern is compatible with a stereoscopic image made of two pieces that show the same scene with just a slight horizontal offset. Further, the lengths of the trajectories (additionally illustrated by the circles' diameters in Figure 1D) are compatible with a depth structure to be expected for the given setting: Areas in the foreground show indeed larger trajectories.

So might the Prado and the Louvre version have been created not simply as original and copy but actually as two halves making a stereoscopic image? Such an assumption is supported by the studio layout as reconstructed in Figure 2. The combination of our participants' averaged estimates of the relative positions of painter and model derived from the Louvre and the Prado version, respectively, results in a difference between the paintings that reflects a disparity value $\Delta = 69.3$ mm (see Figure 2). Interestingly, this is only slightly (but not significantly, $z = 1.1$, $p = .1293$, *n.s.*) above the average inter-ocular distance of Italian males (i.e., 64.1 mm, see Farkas et al 2005). The two *Mona Lisas*, it seems, were executed under spatial conditions that mimic human binocular vision. The trajectories present

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in upper parts of *Mona Lisa*'s depiction (i.e. face, hair, left body), however, are rather at odds with the stereo pair assumption. They form a pattern that is in itself consistent but, in contrast to the trajectories present in the lower image area, they are mainly in accord with a vertical, slightly rightward displacement. Maybe this pattern is an unwanted spin-off from the specific positions the painters took. As illustrated in Figure 2, these differed not only in direction but also in distance to the model, which yielded vertical perspectival changes.

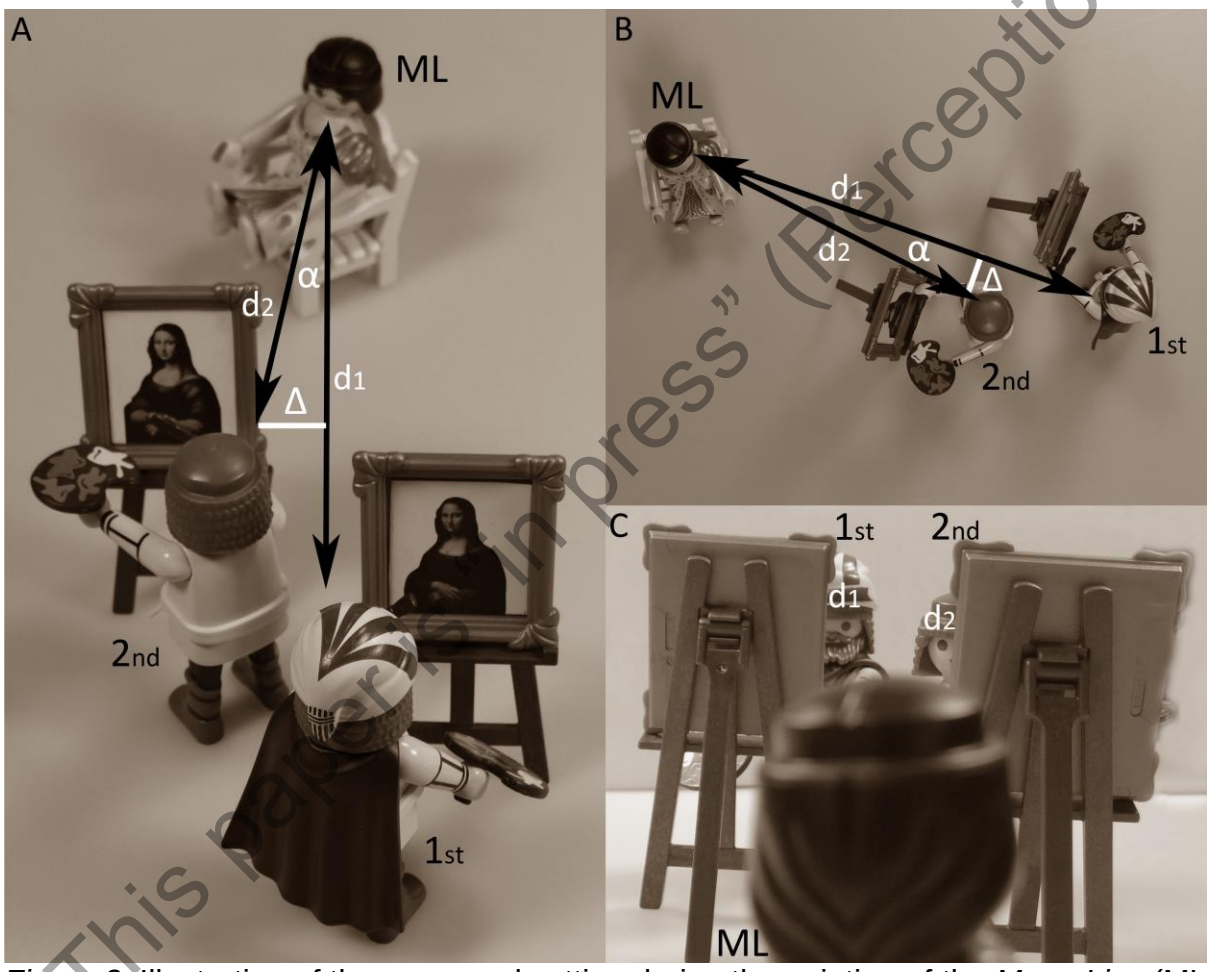

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Figure 2. Illustration of the supposed setting during the painting of the *Mona Lisa* (ML stands for Mona Lisa, the portrayed person; 1st = painter of the Louvre version; 2nd = painter of the Prado version): d_1 and d_2 indicate the distances between ML and the 1st and the 2nd painter, respectively, while α provides the angle between the two different perspectives; Δ indicates the disparity that would arise between the different perspectives, if both artists were at the same spatial distance d_2 from the model. Note: Due to the very acute angle α and the physical dimensions of the painters' bodies, they could not directly "reproduce" the human inter-ocular distance while painting and standing in juxtaposition (side by side) with each other. To compensate for the resulting larger horizontal disparity between their perspectives, the two painters had to take positions that also differed in distance from the model (indicated by d_1 and d_2) in order to nevertheless mimic the interocular distance.

Leonardo, binocular vision and stereo images

One main topic Leonardo picked up on repeatedly is the difference between monocular and binocular vision (Wade and Ono 2012) and the related problem of reproducing natural relief or depth on the painter's canvas (Wade et al 2001). Leonardo realized that "see(ing) one object behind another" is possible in binocular vision as the nearer object occludes different parts of the more distant one (e.g. the background) depending on whether seen with the left or the right eye (Wade et al 2001). There is, however, yet no indication that he ever took the final step to concluding that the visual fields' disparity itself is the basis of depth perception or *stereopsis* (Wade et al 2001). This step was not taken until Wheatstone's remarks on binocular vision and his invention of the *stereoscope* in the 1830s (see Wade 1987; Wheatstone 1838). Wheatstone's apparatus, together with the means to get multiple very accurate depictions of the same object as offered by photography, made possible what Leonardo had sought for: the generation of images that realistically represent binocular relief or depth perception.

It is hard to believe that Leonardo, this quintessential Renaissance mind, had a clue about horizontal disparity in binocular vision but was content with merely describing the problem this phenomenon poses to the painter instead of trying to also understand or explain its function. According to Wheatstone (1838), this "failure" is based on an unfortunate choice of illustration: Leonardo used a sphere to demonstrate the different fields of occlusion projected on both eyes. A less symmetrical, more complexly shaped object would have easily forced his attention to that much more important phenomenon of 3D vision, the disparity between the two retinal images. For the purpose of a little thought experiment, let us assume that Leonardo finally did get the point mentioned by Wheatstone (which still is within the realms of possibility, at least). It is, then, rather conceivable that he also tried to utilise this

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knowledge and aimed at creating a realistic representation or simulation of depth perception, meaning some kind of stereoscopic image. In order to obtain such an image he would have had to produce two accurate depictions of the same scene that only differed slightly with regard to perspective (in order to reproduce human inter-ocular distance), to be presented side by side so that the recipient was able to look at with the eyes converged in front of them or by use of parallel view (depending on the depictions' width and positioning, see Dodgson 2004). The above data suggest that the Louvre-Prado double does meet these requirements (not perfectly, even though one has to bear in mind that these are not photographed but were painted half a millennium ago)—so, maybe the double was really designed as a stereo pair. Most likely, would then also be the first stereoscopic image known in history, produced even earlier than the Chimenti sketches once misunderstood as being stereoscopic (for a critical discussion, see Wade 2003). The anaglyphs (Figure 3: for the face, Figure 4: for the hands) and the 3D reconstruction shown in Figure 5 give an impression of the stereoscopic quality of the Louvre-Prado combination. Whether this quality was actually created by intention or by accident can, of course, not be said for sure—but in the case of Leonardo you never know.

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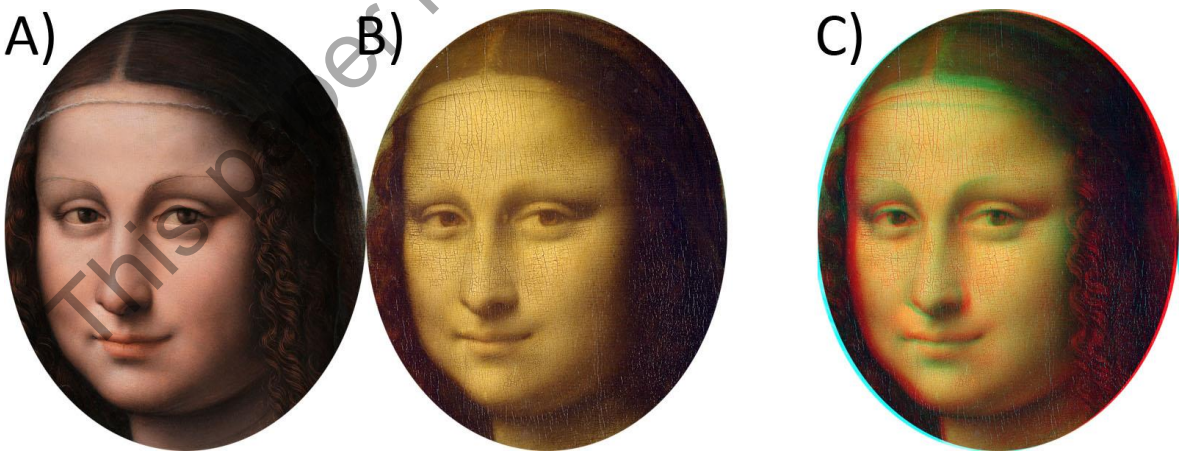

Figure 3. Detailed view on the face regions of the Prado (A) and the Louvre (B) version plus a red-cyan anaglyph (C) combining both depictions.

Figure 4. Detailed view on the hands regions of the Prado (A) and the Louvre (B) version plus a red-cyan anaglyph (C) combining both depictions. The colours of the Prado version have been adjusted to the Louvre version.

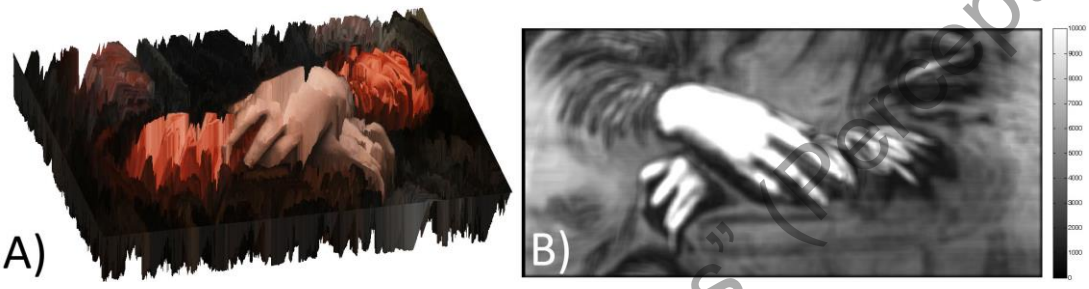

Figure 5. 3D reconstruction (A) and matching costs (B) of the hands region via Fast Matlab Stereo Matching Algorithm by Wim Abbeloos. An animated 3D reconstruction based on this algorithm is presented in the supplemental material.

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Authors' contributions

Both authors contributed to the study concept and design. Testing and data collection were performed by two student researchers working at the Department of General Psychology and Methodology, University of Bamberg, under the supervision of VMH. CCC performed the data analysis and created the figures. Both authors drafted the paper and approved the final version of the paper for submission.

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