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SHORT REPORT

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, rediscovered 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 (thirty-two 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.

Keywords: art and perception, empirical aesthetics, the *Mona Lisa*, stereopsis, 3-D images, bidimensional regression

1 Introduction

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" (page 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 the *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").

2 *Mona Lisa* now and then

In the Renaissance days the *Mona Lisa* [painted 1503–06 and later (Zöllner and Nathan 2011)] looked quite different from how she looks today. In all probability, the coloration was significantly fresher and the background was 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 revealed 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 ultrathin, superimposed layers, in order to shape the *Mona Lisa*'s face, for instance.

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This sophisticated use of the so-called *sfumato* created particularly "soft transitions from light to shade" and a "luminous and tangible" impression (Ruhemann 1961, pages 233–234). Concerning the subject, Leonardo further attained an innovative implementation that expanded the (bust) portrait tradition prevalent in Italy in those days (eg 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').

3 The (rediscovered) 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).

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	around 1500 (?)
Prado *Mona Lisa* (*La Gioconda Velata*)	Museo del Prado, Madrid	ca. 1503
Reynolds *Mona Lisa*	private collection (exhibition at Dulwich Picture Gallery, London in 2006/07)	early 17th century
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, MD	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 bidimensional regression analysis approach (BiDimRegression *R* algorithm) to compare the two paintings (Euclidean solution: $R^2 = 0.998$, with $F_{2,68} = 20\,089.2$, $p < 0.0001$). Multiple analyses performed by the Museo del Prado further revealed that the close resemblance of the Prado and Louvre versions is not limited to the superficial appearance (Prado Museum 2012). By comparison of the respective infrared reflectography results, something interesting became visible: the genesis of the Louvre version is almost completely repeated in the Prado version—in fact, from the preparatory drawing to the upper paint layers. Even specific corrections (eg 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.

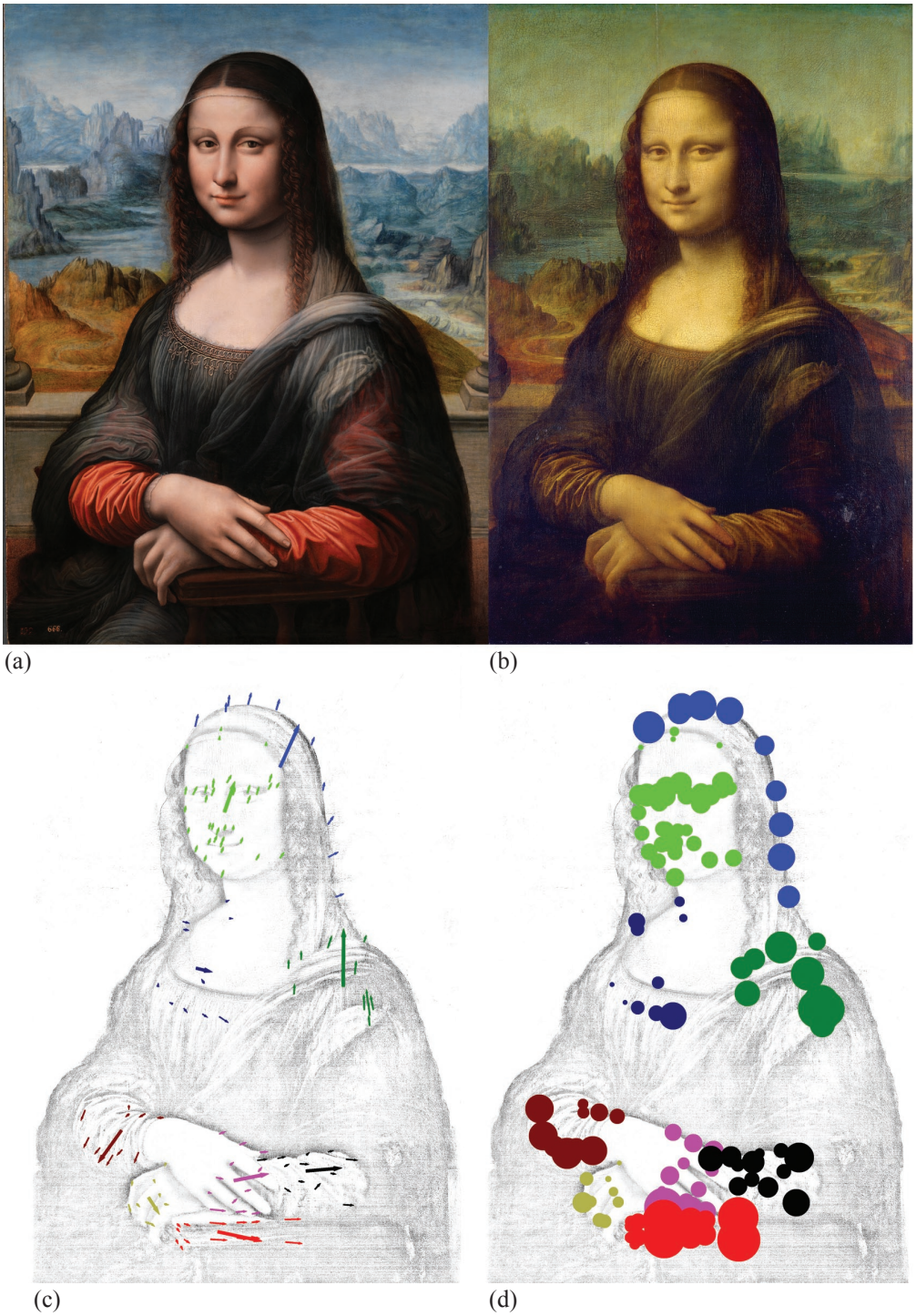


Figure 1. Two times Lisa: the famous *Mona Lisa* exhibited in (b) the Louvre, Paris and her sister painting in (a) the Prado, Madrid. The perspectival change between them is visualized by linear trajectories (c) between the corresponding landmarks set in the Louvre and the Prado versions, respectively, with the Louvre coordinates taken as starting points. The $N = 124$ trajectories are organized into 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).

4 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 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 thirty-two participants (twenty-six female; age $M = 21.3$ years, SD = 2.7 years) to closely inspect the Louvre and the Prado versions 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 with 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 versus 4.0° for the Prado version, $p = 0.0006$, $d = 0.694$; note that 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 versus 2.1 m for the Prado version, $p = 0.0012$, $d = 0.661$). Figure 1 visualizes the perspectival difference in question as calculated by means of linear trajectories (figures 1c and 1d) between unambiguously corresponding landmarks that we set in the Louvre version (figure 1a) and the Prado version (figure 1b), respectively (the landmarks were organized in nine different categories—for example, 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 the basis of the paintings.

5 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 the Louvre and Prado versions. Importantly, this difference does not seem to be of random but of systematic nature. As figure 1c illustrates, the lower image area (ie 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 indeed show larger trajectories.

So might the Prado and the Louvre versions 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 versions, respectively, results in a difference between the paintings that reflects a disparity value of $\Delta = 69.3$ mm (see figure 2). Interestingly, this is only slightly (but not significantly; $z = 1.1$, $p = 0.1293$, ns) above the average interocular distance of Italian males [ie 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 in the upper parts of *Mona Lisa*'s depiction (ie 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 in accord with mainly 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.

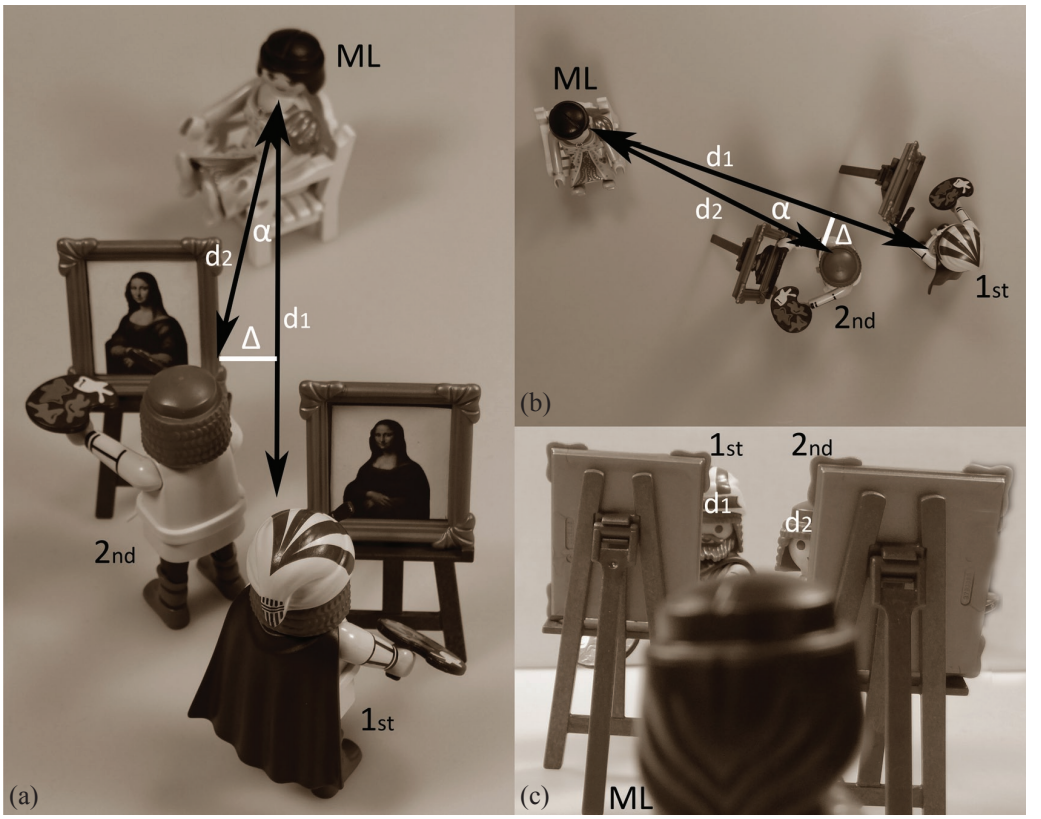


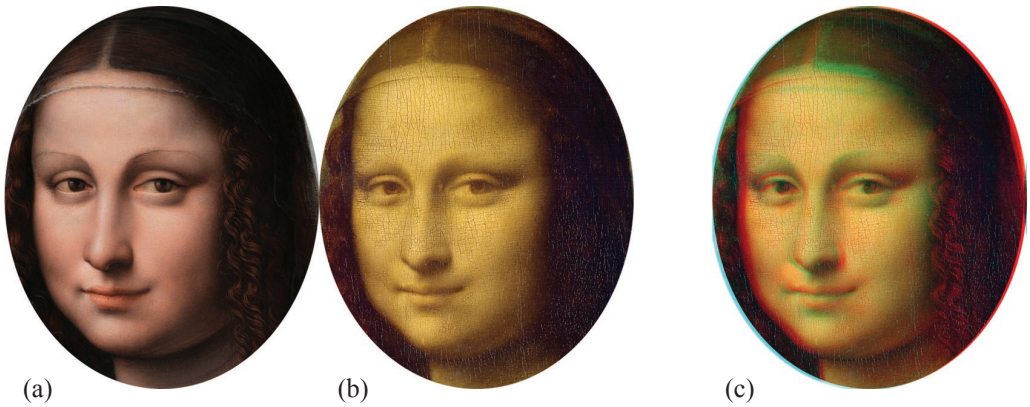
Figure 2. (a)–(c) The supposed setting during the painting of the *Mona Lisa* (ML stands for *Mona Lisa*, the portrayed person; 1st = painter of the Louvre version; 2nd = painter of the Prado version): d_1 and d_2 indicate the distances between ML and the 1st and the 2nd painters, respectively, while 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: Owing to the very acute angle α and the physical dimensions of the painters' bodies, they could not directly 'reproduce' the human interocular 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 mimic the interocular distance.

6 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" (page 232) is possible in binocular vision, as the nearer object occludes different parts of the more distant one (eg the background) depending on whether seen with the left or the right eye. There is, however, yet no indication that he ever took the final step to concluding that the disparity between the visual fields 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).

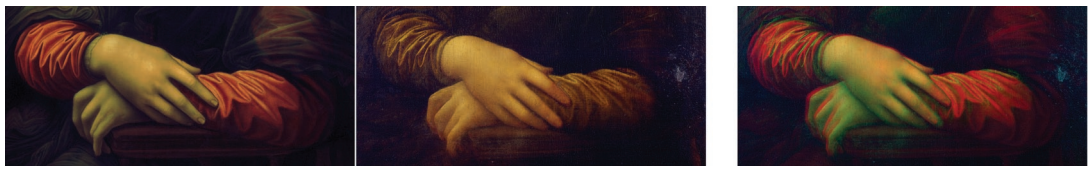
Wheatstone's apparatus, together with the means to get multiple, very accurate depictions of the same object as offered by photography, made possible what Leonardo had sought for: the generation of images that realistically represent binocular relief or depth perception.

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 3-D vision, the disparity between the two retinal images. For the purpose of a little thought experiment, let us assume that Leonardo finally did get to 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 utilize this knowledge



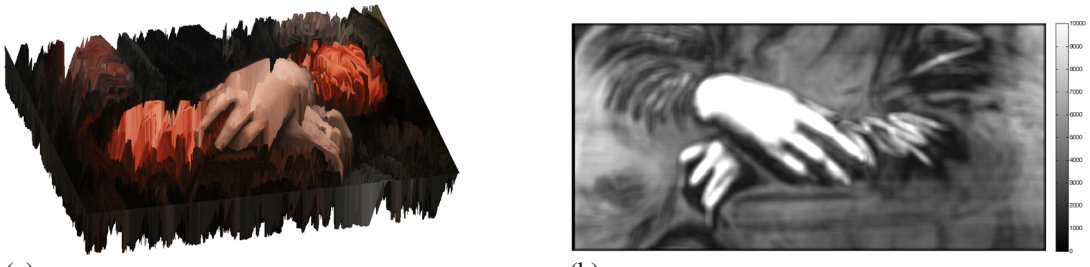
(a) (b) (c)

Figure 3. Detailed view of the face regions of (a) the Prado and (b) the Louvre versions and a red–cyan anaglyph (c) combining both depictions.



(a) (b) (c)

Figure 4. Detailed view of the hand regions of (a) the Prado and (b) the Louvre versions and a red–cyan anaglyph (c) combining both depictions. The colours of the Prado version have been adjusted to the Louvre version.



(a) (b)

Figure 5. (a) 3-D reconstruction and (b) matching costs of the hand regions via the Fast Matlab Stereo Matching Algorithm by Wim Abbeloos. An animated 3-D reconstruction based on this algorithm is presented in the supplemental material.

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 interocular distance), to be presented side by side so that the recipient was able to look at it 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, it 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 (see figure 3 for the face and figure 4 for the hands) and the 3-D 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.

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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