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Painting Restoration and the Eye of the Beholder: A Mobile Eye-Tracking Study at the Unterlinden Museum

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Abstract

Art historical literature has often discussed the impact of painting restorations on viewers. Although many theoretical hypotheses have been proposed regarding the effect of restoration on the beholder's eye, little empirical research has addressed this topic. This study aimed to fill this gap by investigating whether painting restoration has a meaningful influence on the visual perception of art viewers at the eye-movement level. Specifically, the study designed a mobile eye-tracking study in an ecologically valid setting — the art museum — to investigate the effects of restoration on ten panels from the *Isenheim Altarpiece* (1512–1516) by Matthias Grünewald, currently displayed at the Unterlinden Museum in France. In this study, 86 museum visitors looked at paintings while wearing eye-tracking glasses before ($n = 43$) and after ($n = 43$) restoration. The following measures were analyzed: (1) Total Viewing Time; (2) Duration of the First Fixation; (3) Relative Fixation Count; (4) Fixation Heat Maps; (5) Time to First Fixation in areas of interest (AOIs). The results suggested that Relative Fixation Count significantly increased after restoration. Conversely, the Total Viewing Time and Duration of the First Fixation did not seem to be significantly affected by restoration. The Heat Maps suggested a broader visual inspection of the images and a more explorative gaze pattern after restoration. Moreover, the Time to First Fixation in AOIs significantly decreased after restoration. These findings provide the first empirical evidence of the impact of restoration on the visual perception of genuine paintings as opposed to reproductions observed in a museum.

Keywords
painting restoration, visual perception, museum study, heritage conservation, Isenheim Altarpiece, Grünewald, eye tracking

1. Introduction

1.1. Restoration Practices in Historical Context

Art restoration is a complex and multifaceted practice that requires reflection on the material conditions, historical functions, and intended perceptions of artworks (Conti and Glanville, 2007). Conservation theorists traditionally differ in terms of the practical aspects and purpose of restoration, such as the limits and degree of intensity of interventions on a painting (Stanley-Price *et al.*, 1996). As such, controversies surrounding painting restorations are numerous in art history, such as the famous disputes over pigment reintegration and visual changes in Leonardo da Vinci's *The Last Supper* and Veronese's *The Wedding at Cana* (Hénaut, 2011; Keck, 1984).

Art historians, critics, and aesthetic philosophers have contributed significantly to academic debates on restoration (De Clercq, 2013). For example, the notion that an artwork should be presented as closely as possible to the artist's original intention is not universally accepted (Dykstra, 1996). In *Le Culte Moderne des Monuments* (1903), Riegl addressed the conflicts associated with cultural heritage conservation between the present and the values of the past. Riegl paved the way for using scientific techniques to support decisions on restorations and reduce disputes on the topic (Reedy and Reedy, 1992; Riegl *et al.*, 2013). In 1938, art historian Kenneth Clark further developed the idea that restoration should consider the state of an artwork and its impact on observers, arguing that deep cleaning may not always favor the viewer's perception.

Viewer centrality further developed throughout the twentieth century. In 1963, Cesare Brandi — the first director of the Italian Central Institute of Restoration (*Istituto Centrale per il Restauro*) — summarized these modern viewpoints in his *Teoria del Restauro*. According to Brandi, an art object is simultaneously *matter* and *image*; matter comprises aspect and structure, whereas image is formed in one's consciousness through perception (Brandi, 2001, pp. 33–34). Therefore, restoration also involves creating favorable conditions for forming images, which arise from what is visible when people look at an art object (Brandi, 2001, p. 39). Following Brandi, restorers have often regarded both material issues and the aesthetic perception of the viewer as relevant factors in their practice (Richmond and Bracker, 2009).

Since the codification of heritage sciences as a field of scientific research, solid scientific knowledge has been increasingly considered a critical element

for conservation and restoration practices (Etter *et al.*, 2020). To analyze the direct effect of conservation on observers, restorers can employ social sciences, neuroscience, and perception sciences to inform their work (Fontoura, 2021; Shimamura and Palmer, 2011). However, despite the extensive research on image perception, empirically studying the effects of conservation on public viewing remains an uncommon practice.

1.2. Eye-Tracking Research on Visual Perception of Art

Knowledge gained through eye-monitoring techniques has contributed to the development of information-processing models that detail the mechanisms and processes underlying art perception (Locher, 2022). Eye tracking is often used in this context to measure visual attention, as its most commonly used parameters — fixations and saccades — are assumed to reflect a viewer's attention (Kapoula *et al.*, 2015; Parkhurst *et al.*, 2002; Van Zoest *et al.*, 2004).

One branch of eye-tracking research aims to create visual attention models based on the salient features of a visual scene. According to some models, visual attention can generally be driven by location, contextual information, or the viewer's task (Birmingham *et al.*, 2009; Serences and Yantis, 2006). Others suggest that attention is driven by low-level features (Itti and Koch, 2000, 2001). Parameters, such as Fixation Duration and Saccade Amplitude, are also affected by changes in saliency, with higher luminance in scene viewing associated with shorter Fixation Duration (Nuthmann, 2017).

Eye tracking has been employed to study saliency in paintings and demonstrate how a painter's pictorial technique can influence the visual exploration of their artwork. For instance, Fontoura and Menu's (2022) study on Amedeo Modigliani's painting technique exemplified this use. The aforementioned eye-tracking studies show that general saliency models can be applied to artistic images; however, this application often involves the digital manipulation of stimuli. For instance, Massaro *et al.* (2012) artificially manipulated the colors of paintings to compare two artistic images: a colored one and a black-and-white one. Therefore, eye tracking can be presumed to measure the attention driven by restoration changes effectively. Additionally, restoration facilitates the direct comparison of two stimuli (before and after restoration) without digital manipulation.

1.3. Eye-Tracking and Painting Restoration

A relevant example of utilizing eye-tracking research to investigate restored images is demonstrated in a study by Locher *et al.* (2020), who employed eye tracking to elucidate the impact of surface cleaning on observers' visual perception. They conducted their experiment in a laboratory using digital reproductions of artworks projected onto a screen. They recruited participants

with little-to-no art knowledge, composed of students and staff. The authors described their study as exploratory and analyzed various eye-tracking parameters, including the duration of the participants' First Fixation, Total Viewing Time, Total Number of Fixations, and Degree of Coverage of the pictorial field. They utilized digital reproductions of ten paintings, the surfaces of which had undergone cleaning at different times, presented in a randomized sequence in both their pre- and post-restoration states. The study found that, for the same group of 15 participants, Fixation Count and Duration, both for the First Fixation and overall, significantly increased after restoration.

The interpretation and discussion of the results of Locher *et al.* (2020) must consider the limitations of using a remote eye tracker and digital reproductions in restoration-related research rather than actual artworks. These constraints include limited access to natural colors, image quality, resolution, size, and format (Reymond *et al.*, 2020). Moreover, it is essential to consider the trade-off between aesthetic experience and experimental control in laboratory versus museum studies. Differences in sustained and focused attention to art have been demonstrated by Brieber *et al.* (2014) and described by Carbon (2020), who emphasized the importance of context in the art experience. Controlled settings, such as experiment rooms, allow for rigorous experimental management and require participants to view images on a screen while standing in front of remote eye-tracking devices. Nevertheless, access to the original artwork and transportation to laboratories pose technical and security challenges. These preconditions have led to the widespread use of reproductions of paintings in eye-tracking studies in art rather than actual paintings themselves.

In addition to flattening the three-dimensional qualities of original paintings, desktop eye trackers used in laboratories prevent people from moving around pieces — a fundamental aspect of the museum experience (Carbon, 2017, 2019; Gibson, 1986). Furthermore, laboratory studies typically fail to account for viewer and museum characteristics and the context in which art is presented (Linden and Wagemans, 2021; Pelowski *et al.*, 2017; Smith *et al.*, 2017). They also disregard the environment in which people's lived experiences occur, particularly those of the aesthetic type (Brady *et al.*, 2018; Dupont, 2007; Pelowski *et al.*, 2018; Schaeffer, 2015). Consequently, the generalizability of laboratory findings to real-world settings is limited, and it is critical to consider these factors when interpreting the results of such studies.

2. The Present Study

Building on the potential of eye-tracking in the study of painting restoration as demonstrated by Locher *et al.* (2020), this study is conceived as a further step in overcoming the limits associated with the laboratory setting. We aimed to investigate the influence of restoration on the visual observation of paintings

before and after the restoration procedure in a museum. To our knowledge, this is the first study conducted on painting restoration outside a laboratory, utilizing genuine paintings instead of reproductions and recruiting museum visitors as on-site participants. As scientists have not reported the impact of restoration on the visual perception of paintings in an ecological context (Felsen and Dan, 2005; Gibson, 1986), we adopted an exploratory approach (Borg and Gall, 1989) similar to that utilized by Locher *et al.* (2020). The findings may help discern the effects of restoration on the visual salience of paintings viewed in a museum.

2.1. Stimuli

Our study focused on an in-depth empirical analysis of the restoration of ten paintings that comprise the *Isenheim Altarpiece* (1512–1516) created by the German painter Matthias Grünewald. This polyptych, considered a masterpiece of Western art, comprises panels of monumental size and a set of sculptures by Niclaus of Haguenau, displayed in an ancient Dominican chapel that is now an exhibition room of the Unterlinden Museum in Colmar, France (Martin *et al.*, 2012). The panels' frames and sculptures were also restored. However, we only focused on the restoration of the paintings, as analyzing the restoration of frames and sculptures requires a distinct experimental design. Here, we concentrated on the two-dimensional panels.

All ten panels of the *Isenheim Altarpiece* depict different scenes from the lives of Christ and Saint Anthony (Béguerie-De Paepe and Menu, 2007). The diversity of the panels enables the analysis of each one as a distinct painting, as they are no longer assembled into a single piece. The panels are displayed separately and evenly distributed throughout the museum chapel, encouraging visitors to move around the space to view the images.

The restoration process for the paintings of the *Isenheim Altarpiece* involved surface cleaning and an aesthetic procedure to remove the old, opaque, and yellowish varnish and replace it with a new, translucent, and brighter one. The cleaning process was associated with preventive and reparative work to consolidate the wooden support of the panels and reintegrate damaged pictorial layers. The primary difference expected before and after restoration was an increased brightness of the pictorial elements. Restorers utilized traditional techniques to remove varnish, manually applying solvents. They chose to preserve the paintings' evolving appearance and not renew them completely but clean and maintain the natural aspect of the matter as it evolved. As the paintings were in excellent overall conservation, the original paint layer was replaced only in a few small parts of the images. Some historical marks were deliberately left visible to maintain a record of the effect of time on the polyptych.

2.2. Hypotheses

This study's central hypothesis was that restoration affects the visual perception of paintings at the level of eye movements owing to enhanced low-level features, such as clarity and brightness. We hypothesized that the restored images would result in increased visual attention. To investigate this assumption, we considered the following parameters: (1) Total Viewing Time, (2) Duration of the First Fixation, (3) Relative Fixation Count, (4) Fixation Heat Maps, and (5) Time to First Fixation in areas of interest (AOIs).

3. Method

The protocol comprised four steps, repeated twice before and after restoration: (1) recruitment of participants on-site; (2) spontaneous observation of the paintings by visitors using a mobile eye-tracking device (Tobii Pro Glasses 2; Tobii AB, Stockholm, Sweden); (3) interviews; (4) questionnaires. In addition to eye-tracking, we conducted qualitative interviews and administered questionnaires to collect information on basic demographics and participant profiles. The ethics committees of PSL Research University and EHESS approved this research.

3.1. Study Design

The period from spring to summer is a crucial time for museum studies involving actual visitors, as tourism is highly concentrated during this period. The before-restoration phase of our study was conducted in July and August 2018 during European summer holidays. The after-restoration phase was conducted during the same period in 2022. The four-year interval between the two phases of the study was due to the time required for the *Isenheim Altarpiece* to be fully restored. Intermediary data collection was also conducted during the restoration in November 2019, during which the unvarnished panels were analyzed. However, this paper only presents the results of the before- and after-restoration phases to allow for a more relevant comparison between the two main restoration phases.

The exhibition chapel at the Unterlinden Museum has an artificial electric lighting system that faces the altarpiece directly and is used throughout the year to ensure constant illumination. Additionally, the museum chapel benefits from natural lighting, resulting in a darker room during autumn and winter and a relatively brighter room during spring and summer. Observations were conducted only during the summer daytime, from 10 am to 5 pm, ensuring similar lighting conditions during both phases of the study.

The first step involved recruiting visitors who arrived at the museum and asking them to participate voluntarily in the study. Participants were recruited

at the museum entrance and asked to participate individually. The Unterlinden Museum helped advertise the experiment inside their premises with banners, local press articles, and social media channels. The only requirement for participation was normal vision without corrective lenses.

In the second step, we individually escorted visitors who agreed to participate in the study to the museum's chapel choir. As mentioned previously, we used the Tobii Pro Glasses 2 (100 Hz) eye-tracking tool, which is wearable and utilizes corneal and pupil reflection methods (Duchowski, 2007; Hammoud, 2008; Hansen and Ji, 2009; Holmqvist *et al.*, 2011). We provided the eye-tracking tool to participants at the entrance of the museum's chapel. Subsequently, the participants were outfitted with the tool and underwent a one-point calibration process, following the manufacturer's instructions, before each observation.

Each participant was instructed to enter the museum's chapel and look at all panels freely for as long as they wanted without taking the eye-tracking glasses off or touching them. The ten panels considered in our study were the only artworks exhibited in the room.

To ensure an environment resembling a realistic museum visit, we prioritized an experimental design that favored visitors' spontaneity during painting observation. Throughout the study, visitors remained alone, and we monitored each visit from a distance using a tablet equipped with Tobii Glass Controller software (version 1.114.20033). After completing their painting observations, the participants were asked to return to the museum's chapel entrance without removing their eye-tracking glasses.

In the third step of the experiment, we invited the participants to one-to-one qualitative interviews, in which they were encouraged to discuss their visual experiences while looking at the paintings freely. Interviews were recorded using a microphone attached to the eye-tracking glasses. The participants were instructed to describe what elicited their greatest attention while observing the paintings.

In the fourth step, we asked the participants to exit the museum's chapel, remove the eye-tracking glasses, and complete a brief questionnaire. The questionnaires were designed using Microsoft Word and printed on paper for participants to complete. The complete questionnaire is presented in Appendix A1. After completing all four steps, the volunteers were thanked for participating in the study and provided with a small souvenir as a token of our appreciation.

3.2. Data Analysis

The evolution of head-mounted eye-tracking technology has enabled the proper and practical use of mobile eye-tracking in museums (Santini *et al.*, 2018).

To ensure data quality, we used the open-access software GlassesViewer (Niehorster *et al.*, 2020) to analyze the Tobii Pro Glasses 2 eye-tracker data. The mean precision was 1.74° (SD = 1.24°), and the data loss was 18%. According to the manufacturer's instructions, the accuracy was 3.05°.

We used Tobii's fixation filter [Tobii I-VT (Fixation)] with the gaze velocity threshold set at 100°/s to determine whether the data should be classified as fixation. Data with a velocity above the threshold were classified as saccades, and data with velocities below the threshold were considered fixations. Heat Maps were created based on the absolute Fixation Count.

We processed the eye-tracking data using Tobii Pro Lab version 1.152.30002 (x64). Gaze-positioning data were automatically mapped onto pictures of the paintings using Tobii's algorithm for real-world mapping, which compares static snapshots of the paintings with picture frames in the recording from the eye-tracking device. Our data cleaning process included manual frame-by-frame correction of the automatically mapped data through visual assessment within the same Tobii Pro Lab software. The data output (.xlsx files) was processed using RStudio. Similarly, the questionnaires were converted to.xlsx files and analyzed using Microsoft Excel.

We used VoyantTools — a web-based, open-source reading and analysis environment for digital texts — to analyze the interview texts (http://voyant-tools.org/). We employed text-mining techniques to identify the most prominent terms used by participants when discussing their visual experience.

3.3. Areas of Interest Design

To define AOIs, we aimed to identify specific areas within paintings that were the most affected by the cleaning process and could elicit different responses from viewers according to the paintings' restorers. These areas varied in semantic content. Some AOIs displayed prominent elements related to the painting's composition and narrative, such as the main characters, essential body parts, wounds, and objects. An equal number of AOIs featured background areas of the painting with little to-no social cues, such as elements of nature, architectural features, and diaphanous elements. We designed the sizes of the AOIs to make them resistant to noise and inaccuracies, with all AOIs being square and equal in size at 130 pixels.

We positioned the squares to frame the core of the object of interest at the center of the AOIs, leaving an extra margin around the target. Although specialized literature suggests that the size of AOIs should cover the entire shape of the figures (Holmqvist *et al.*, 2011, pp. 218–220), we decided to frame only the segments judged to be the most important for each target object. We positioned the different AOIs such that they did not overlap. To ensure that fixations directed to one area were not detected in an adjacent area, we set a

minimum space corresponding to the accuracy rate between the AOIs ($M = 1.74°$, SD = 1.24°; $M = 14$ pixels², SD = 6.75 pixels²). We added an additional margin of 3° (i.e., double the average precision rate) to the space between the different AOIs to ensure that fixations from different areas did not mix. We designed the AOIs using the Tobii Pro Lab software. Figure A1 in Appendix A2 presents the AOIs and describes the elements of interest for each.

3.4. Participants

Of the 126 participants who completed the protocol, 40 were excluded from the analysis because of insufficient data quality (precision less than 1.74°, SD = 1.24°), as described in Section *3.2. Data Analysis*. Thus, we retained the recordings of 86 volunteers whose data sets were complete and of good quality. Half of the participants ($n = 43$) participated in the study before restoration, and the other half participated afterward ($n = 43$).

In both the before- and after-restoration phases of the study, the participants' profiles were comparable in terms of age ($M_{Before} = 38$ years, SD = 19; $M_{After} = 40$ years, SD = 20) and country of origin (before: 70% European, 26% from the Americas, 2% Asian, and 2% from Oceania; after: 79% European, 16% from the Americas, 5% Asian, and 0% from Oceania). The distribution of sex profiles was different before and after restoration (before: 65% male, 35% female; after: 37% male, 63% female). Most participants had a high education degree (before, 65%; after, 90%) and reported a medium or lower self-evaluation of their art knowledge (as in the questionnaire in Appendix A1) (before, 65%; after, 72%). Finally, although most participants had heard of the artwork before the experiment (before, 60%; after, 49%), few had heard of the artist (before, 37%; after, 37%).

4. Results

4.1. Total Viewing Time

We measured the Total Viewing Time as the sum of Fixation Durations for all paintings. Overall, we found no significant difference in the mean values for the paintings' Total Viewing Time between the restoration conditions ($M_{Before} = 216.33$ s; $M_{After} = 186.24$ s; $SD_{Before} = 132.11$ s; $SD_{After} = 177.64$ s; $t(84) = 0.89$; $p = 0.37$).

Nevertheless, the mean values for the Total Duration of Visits (i.e., the amount of time that people spent spontaneously in the museum's chapel during their visits — the duration of the experiment — regardless of whether they were looking at the paintings) were significantly different for the restored versus unrestored images ($M_{Before} = 590.90$ s; $M_{After} = 434.86$ s, $SD_{Before} = 326.40$ s, $SD_{After} = 291.37$ s, $t(82) = 2.33$, $p = 0.02$).

4.2. Duration of the First Fixation

Figure 1 shows the results for the Duration of the First Fixation averaged across all panels before and after restoration ($M_{\text{Before}} = 163.62$ ms; $M_{\text{After}} = 156.86$ ms; $\text{SD}_{\text{Before}} = 41.65$ ms; $\text{SD}_{\text{After}} = 51.78$ ms). A *t*-test indicated no significant difference in the mean values between the before and after conditions: $t(84) = 0.66$; $p = 0.50$.

4.3. Relative Fixation Count

Figure 2 depicts the overall changes in the Relative Fixation Count, defined as the Number of Fixations on the paintings divided by the Total Duration of Visits in seconds for all paintings before and after restoration. The results showed a significant increase in the Relative Fixation Count in the paintings after restoration ($M_{\text{Before}} = 1.47$ fix/s; $M_{\text{After}} = 1.65$ fix/s; $\text{SD}_{\text{Before}} = 0.42$ fix/s; $\text{SD}_{\text{After}} = 0.39$ fix/s), confirmed by a *t*-test between two independent samples: $t(84) = -2.08$, $p = 0.04$.

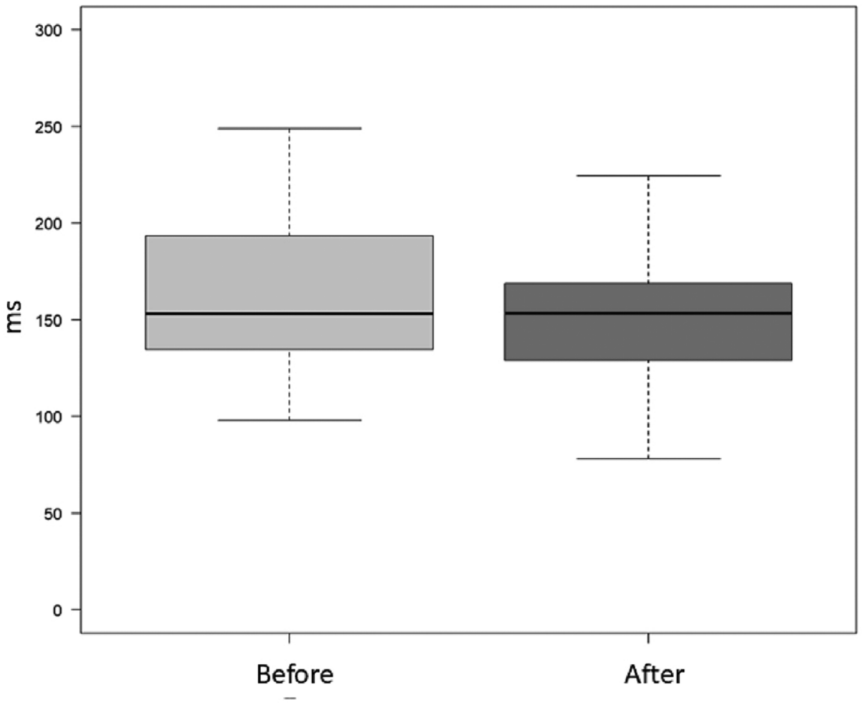

Figure 1. Duration of the First Fixation (ms).

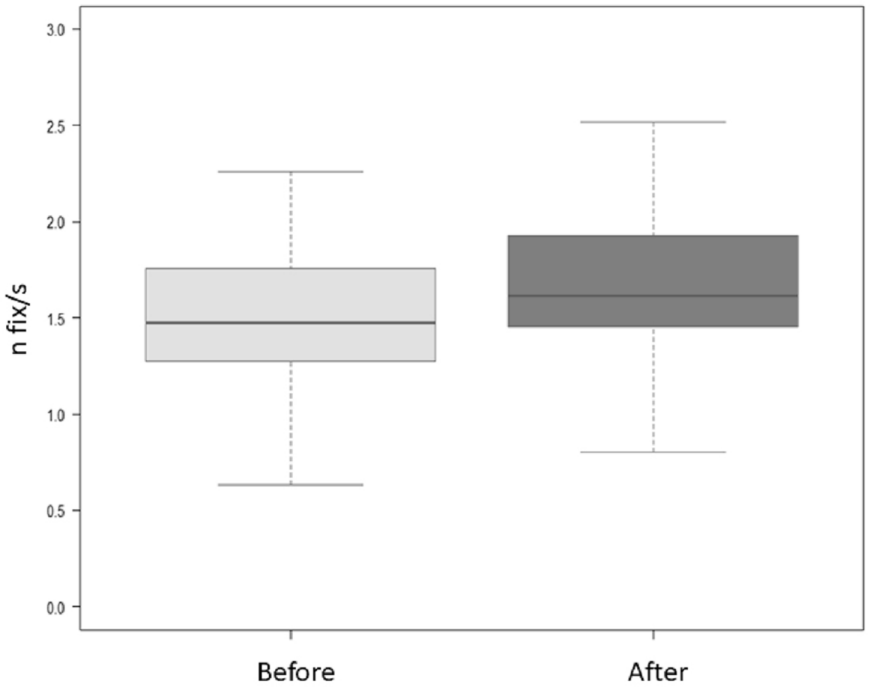

Figure 2. Relative Fixation Count averaged across paintings before and after restoration (fix/s).

4.4. Fixation Heat Maps

The Fixation Heat Maps — generated based on the absolute Fixation Count detected on specific parts of the panels — illustrate the fixations' coverage on the painting surface across time. In this study, we compared Heat Maps for the before- and after-restoration conditions on a descriptive basis.

The results showed that the core of interest did not change considerably before and after the cleaning procedure. However, the concentration of fixations either expanded or shifted around salient core zones after restoration. New zones of interest also appeared, mainly on the backgrounds, objects, and the characters' body parts and clothes, suggesting a broader visual observation of the images after restoration (Fig. 3). The expansion of salient zones revealed by the Fixation Heat Maps indicated that people took a more explorative approach to images after restoration, affirming our results in Section 4.3. *Relative Fixation Count*.

4.5. Time to First Fixation in Areas of Interest

The Time to First Fixation in AOIs elucidates the speed at which a viewer's attention is elicited by a specific stimulus. Figure 4 shows changes in Time to

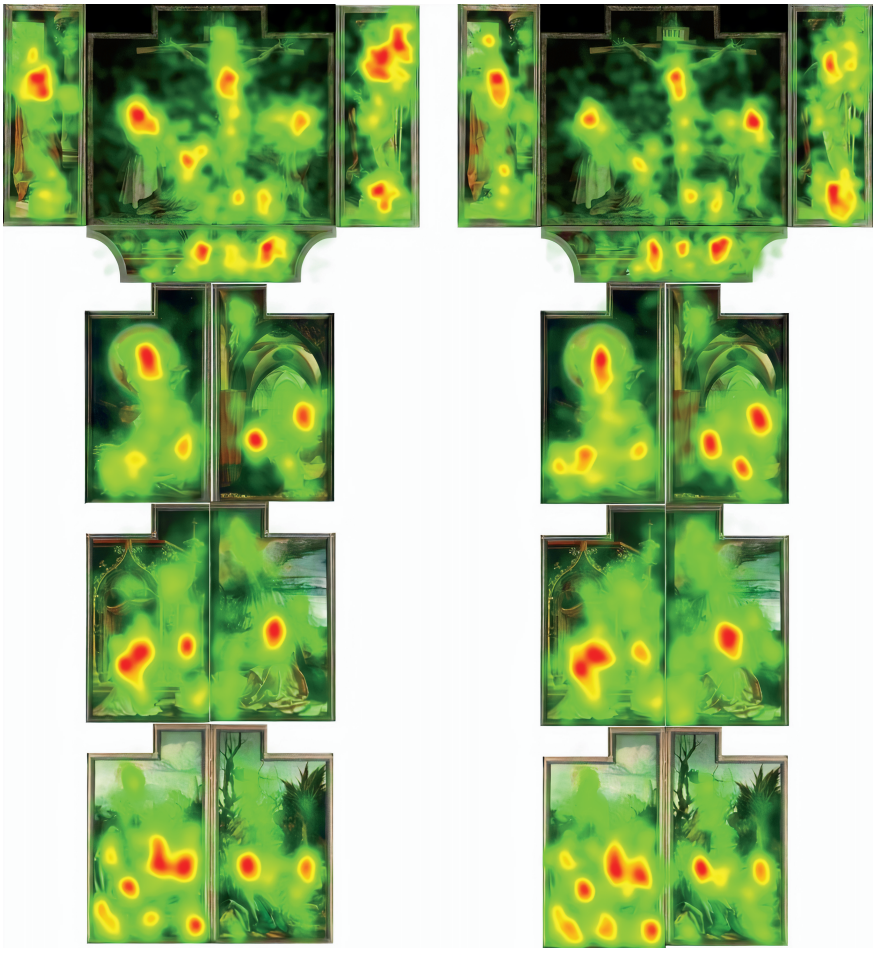

Figure 3. Fixation Count Heat Maps (*n* fix), before (left column) and after (right column) restoration.

First Fixation (ms), before and after restoration, summed for all AOIs (M_{Before} = 12,644.21 ms; M_{After} = 8,850.33 ms; $\text{SD}_{\text{Before}}$ = 9,213.37 ms; SD_{After} = 7,336.50 ms). A *t*-test between two independent samples indicated a significant difference between the mean Time to First Fixation in AOIs before and after restoration ($t(84) = 2.12$, $p = 0.03$).

5. Discussion

Our study revealed that participants did not allocate most of their Total Duration of Visits to the museum's chapel to observe the paintings directly,

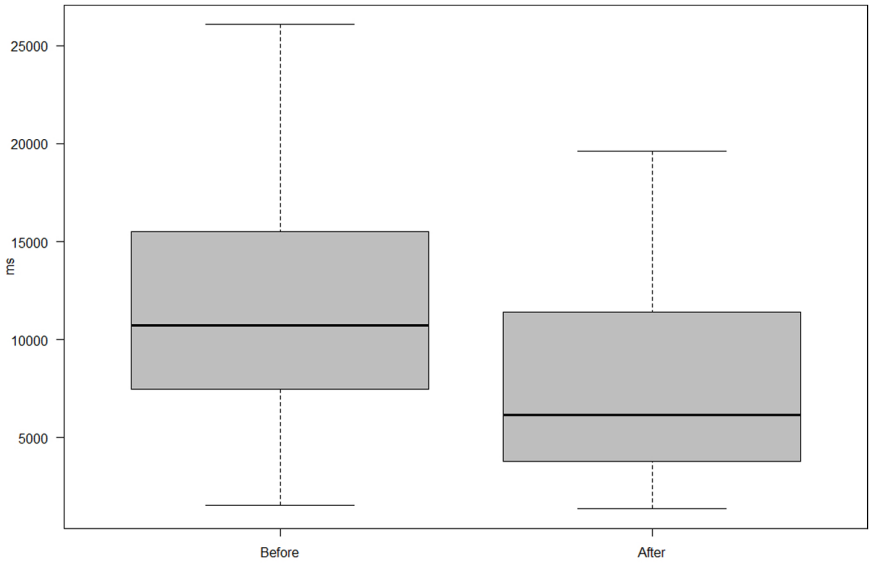

Figure 4. Time to First Fixation in areas of interest (ms).

regardless of restoration condition (Total Duration of Visits dedicated to looking at the paintings: before, 36.61%; after, 42.82%). Additionally, the mean values for the Total Duration of Visits decreased significantly after restoration. One explanation is that the improved clarity of the images may have diverted participants' attention from other elements in the museum room to the images, leading to the faster completion of the study task. Alternatively, other factors unrelated to the restoration — but linked to the participants' environment — may have most likely influenced the spontaneous time spent in the museum chapel. For instance, the social setting in which the artworks are viewed, as described by Smith *et al.* (2017) and Carbon (2019), may have played a role in the Total Duration of Visits. The recent lifting of all COVID-19 health restrictions, which occurred several weeks before the second phase of our study, may have impacted the amount of time participants were willing to spend in the museum chapel during the experiment. However, this explanation is post hoc and impossible to verify.

Contrary to the results of Locher *et al.* (2020), our data indicated that the mean values for the paintings' Total Viewing Time were not significantly different between the restored and unrestored panels in the museum. Therefore, although the restoration or other social settings could have contributed to a significantly shorter Total Duration of Visits to the museum chapel, they did not affect the time participants spent directly observing the paintings. One possible explanation is that not all restoration procedures affect visitors'

perceptions. Extreme restoration–cleaning techniques are more likely to elicit prolonged viewing times. Conversely, subtle and discrete restoration techniques would tend to result in minor or no changes. For example, the *Isenheim Altarpiece* panels underwent extensive light restoration that did not drastically alter their overall appearance. Nevertheless, the degree of restoration intensity performed on the paintings used in the study of Locher *et al.* (2020) is unknown and could account for the disparate results between the two studies.

Furthermore, contrary to the results of Locher *et al.* (2020), the Duration of the First Fixation was not significantly affected by restoration. Such discrepancy has several possible explanations. Locher *et al.* (2020) presented a set of ten digital stimuli before and after restoration in a randomized sequence. Their stimuli set included repeating the same painting twice for the same viewer (once before and once after restoration), which might have created different expectations for the participants and caused a prolonged First Fixation. Moreover, as Locher *et al.* (2020) presented the images on a screen, they appeared wholly and entirely for the seated observer throughout the visualization. Conversely, in museum conditions, participants can move and choose their preferred angle and distance from the painting at any time.

Additionally, museum settings and other interferences may influence museum painting visualization (Carbon, 2020; Linden and Wagemans, 2021). All these explanations highlight the need for more systematic eye-tracking research on painting restoration with an explicit, systematic comparison between laboratory and museum conditions, which would help clarify the limitations of each method.

Following restoration, the data showed a significant increase in the Relative Fixation Count, indicating that the panels received more fixations in general during visits, possibly owing to the enhanced brightness resulting from the restoration procedure. Moreover, the expanded salient zones on Fixation Count Heat Maps indicated that people adopted a more exploratory approach to the images after restoration. These findings aligned with those reported by Locher *et al.* (2020) and, more specifically, the investigation by Quian Quiroga *et al.* (2011), which revealed a broader visual exploration of images in museum observations, particularly in regions of interest surrounding characters. Nonetheless, in our study, visual exploration also increased in areas pertaining to objects and minutiae in the backgrounds of the paintings.

The significant decrease found in the mean values for Time to First Fixation within AOIs after restoration suggested that visitors could quickly identify and focus on critical areas of paintings where major restoration effects were expected to be perceived. Furthermore, the larger observed areas identified in the Heat Maps reinforced the assumption that restoration can reveal a significant amount of previously concealed information.

We hypothesized that people's visual behavior in a museum would change after a painting's restoration. Although some of our eye-tracking results supported this hypothesis, not all parameters aligned with those observed by Locher *et al.* (2020). The implications of these changes for the viewer's conscious perception cannot be assessed with eye tracking alone. Consciousness is a complex phenomenological process that can be preliminarily estimated through qualitative results and by associating verbal reports (Ericsson and Simon, 1980) with eye-movement data (Bauer and Schwan, 2018; Locher *et al.*, 2007), in line with research on empirical aesthetics and consciousness (Ansorge *et al.*, 2022).

We expected the participants' responses to the questionnaire to provide insights regarding this matter. For example, the number of 'strongly agree' responses to the statement "This painting is interesting" slightly increased after restoration (before, 25; after, 28). Similarly, the number of 'strongly agree' responses to the statements "This painting stimulated my imagination" (before, 12; after, 15) and "I was moved" (before, 8; after, 13) increased after restoration as well. Additionally, the overall responses of 'agree' to these three statements remained high after restoration, contrary to limited responses of 'neither agree nor disagree,' 'disagree,' and 'strongly disagree,' as depicted in Figure A2 in Appendix A3. Thus, viewing restored paintings in museums may have a subtle impact on visitors' typical aesthetic responses, such as emotions, imagination, and interest.

The interviews further provided additional insights. For example, the term 'color' was mentioned similarly before and after restoration, indicating that visitors generally perceived the chromatic qualities of the polyptych regardless of its restoration status. Moreover, the participants' general comments on the paintings showed subtle, but not substantial changes after restoration. However, given that we did not focus on a qualitative analysis, a more comprehensive investigation is recommended for future research endeavors.

6. Conclusion

This study attempted to empirically assess the effects of painting restorations on museum visitors and their visual perceptions. Specifically, we discussed the effects of a cleaning procedure that thinned the varnish layer and enhanced the clarity of ten oil paintings. To our knowledge, this is the first eye-tracking study conducted in an ecologically valid setting using restored actual paintings rather than digital reproductions.

We reported significant results for two groups of 43 participants regarding Relative Fixation Count and Time to First Fixation in AOIs. Our findings suggested that Total Viewing Time was not necessarily affected by the

restoration. Nevertheless, after restoration, paintings seemed to elicit more fixation, and viewers looked at more extensive areas of the paintings. These results call for further clarification of the implications of such changes at the cognitive level through in-depth qualitative and quantitative data analyses.

Although some of our research questions were exploratory, this study provided an innovative methodological approach, the relevance of which should not be underestimated. As mentioned, modern restoration practices must fulfill multiple needs, facing material, technical, historical, and aesthetic questions. Amid the complexity of painting restoration, this study suggested one more field of scientific groundwork. By providing tangible insights into viewers' perceptions, this and future research can build the basis of productive communication between the viewing public, art historians, and restorers based on empirical knowledge.

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Appendix A1 — Questionnaire

English Version

Please answer the following questions based on your observation of the *Isenheim Altarpiece* wearing eye-tracking glasses.

1. Classify the sentences below based on your visit. Please choose one option only.
   a. *I was moved* (Strongly disagree/Disagree/Neither agree nor disagree/Agree/Strongly agree)
   b. *This painting stimulated my imagination* (Strongly disagree/Disagree/Neither agree nor disagree/Agree/Strongly agree)
   c. *This painting is Interesting* (Strongly disagree/Disagree/Neither agree nor disagree/Agree/Strongly agree)
2. Did you know about the *Isenheim Altarpiece* before? Please choose one option only (Yes/No)
3. The *Isenheim Altarpiece* was painted by Matthias Grünewald. Did you know this artist before? Please choose one option only (Yes/No)
4. On a scale of 1 to 5, how would you rate your level of knowledge in the arts? (1 = No knowledge at all; 5 = Extensive knowledge)
5. What is your age?
6. What is your sex (male/female/other)?
7. What is your nationality?
8. What is your educational background? Please choose one option (No diploma/College/Technical degree/Baccalaureate/Baccalaureate+2/Bachelor's/Master's/PhD)

Thank you.

French Version

Veuillez répondre aux questions suivantes en fonction de votre observation du *Retable d'Issenheim* portant des lunettes d'oculométrie.

1. Classez les phrases ci-dessous en fonction de votre visite. Veuillez choisir une seule option.
   a. J'ai été ému (Tout à fait en désaccord/En désaccord/Ni d'accord ni en désaccord/Tout à fait d'accord)
   b. Ce tableau a stimulé mon imagination (Fortement en désaccord/En désaccord/Ni d'accord ni en désaccord/Tout à fait d'accord)
   c. Ce tableau est intéressant (Tout à fait en désaccord/En désaccord/Ni d'accord ni en désaccord/Tout à fait d'accord)

2. Avez-vous déjà entendu parler du *Retable d'Issenheim*? Veuillez choisir une seule option (Oui/Non)
3. Le *Retable d'Issenheim* a été peint par Matthias Grünewald. Connaissiez-vous cet artiste avant? Veuillez choisir une seule option (Oui/Non)
4. Sur une échelle de 1 à 5, comment évalueriez-vous votre niveau de connaissance dans les arts? (1 = Aucune connaissance; 5 = Connaissance étendue)
5. Quel est votre âge?
6. Quel est votre sexe (homme/femme/autre)?
7. Quelle est votre nationalité?
8. Quelle est votre formation? Veuillez choisir une option (Pas de diplôme/collège/diplôme technique/baccalauréat/baccalauréat+2/licence/master/doctorat)

Merci.

Appendix A2

Figure A1. Areas of interest drawn on the paintings. Matthias Grünewald, *The Isenheim Altarpiece*, 1512–1516, oil on wood, 269 × 307 cm (total opening), Colmar, Unterlinden Museum. Photo credit: Unterlinden Museum.

Primary AOI Zones (P)

(P)01 = Primary_Annunciation_Angel Gabriel's face and wing
(P)02 = Primary_Annunciation_Mary
(P)03 = Primary_St. Anthony_Drape
(P)04 = Primary_St. Anthony_Left hand
(P)05 = Primary_St. Anthony_Right hand
(P)06 = Primary_St. Anthony_Saint Anthony's face
(P)07 = Primary_Concert_Characters
(P)08 = Primary_Concert_Mary
(P)09 = Primary_Concert_Musician Angel's face
(P)10 = Primary_Crucifixion_Calice
(P)11 = Primary_Crucifixion_Christ's abdomen
(P)12 = Primary_Crucifixion_Christ's face
(P)13 = Primary_Crucifixion_Christ's feet
(P)14 = Primary_Crucifixion_Christ's knees
(P)15 = Primary_Crucifixion_John Baptiste's finger
(P)16 = Primary_Crucifixion_Left hand
(P)17 = Primary_Crucifixion_Magdalene
(P)18 = Primary_Crucifixion_Magdalene's hair
(P)19 = Primary_Crucifixion_Mary and Evangelist's hands
(P)20 = Primary_Crucifixion_Jar
(P)21 = Primary_Nativity_God/Sun
(P)22 = Primary_Nativity_Jesus and Mary's face
(P)23 = Primary_Predella_Christ's chest/Belly
(P)24 = Primary_Predella_Christ's feet
(P)25 = Primary_Predella_Magdalene
(P)26 = Primary_Predella_Mary
(P)27 = Primary_Resurrection_Christ's face
(P)28 = Primary_Resurrection_Christ's feet
(P)29 = Primary_St. Sebastian_Arrows legs
(P)30 = Primary_St. Sebastian_Saint Sebastian's hands
(P)31 = Primary_Temptation_Bird monster
(P)32 = Primary_Temptation_Bottom central monster/Hand
(P)33 = Primary_Temptation_Bottom right monster
(P)34 = Primary_Temptation_Central monsters
(P)35 = Primary_Temptation_God/Sun
(P)35 = Primary_Temptation_Left monsters
(P)37 = Primary_Temptation_Right central Monsters
(P)38 = Primary_Visit_St. Anthony
(P)39 = Primary_Visit_St. Paul

Secondary AOI Zones (S)

(S)01 = Secondary_Annonciation_Book
(S)02 = Secondary_Annunciation_Ceiling
(S)03 = Secondary_Annunciation_Dove
(S)04 = Secondary_Annunciation_Moses
(S)05 = Secondary_ St Anthony_Pedestal base
(S)06 = Secondary_ St Anthony_Top window/Demon
(S)07 = Secondary_Concert_Angels background
(S)08 = Secondary_Concert_Canopy lateral
(S)09 = Secondary_Concert_Musician's color gradient
(S)10 = Secondary_Concert_Jar/Bucket
(S)11 = Secondary_Crucifixion_Book
(S)12 = Secondary_Crucifixion_Central background
(S)13 = Secondary_Crucifixion_Rock
(S)14 = Secondary_Nativity_Angels/Sky
(S)15 = Secondary_Nativity_Bed/Jar
(S)16 = Secondary_Nativity_Gate/Wall
(S)17 = Secondary_Nativity_Mary's drape
(S)18 = Secondary_Nativity_Roses
(S)19 = Secondary_Nativity_Sky
(S)20 = Secondary_Nativity_Tree
(S)21 = Secondary_Predella_Crown of thorns
(S)22 = Secondary_Predella_Right background
(S)23 = Secondary_Resurrection_Bottom right soldier
(S)24 = Secondary_Resurrection_Left bush/Foot
(S)25 = Secondary_Resurrection_Left drape gradient
(S)26 = Secondary_Resurrection_Left top background
(S)27 = Secondary_Resurrection_Middle background
(S)28 = Secondary_ St. Sebastian_Angels window
(S)29 = Secondary_St. Sebastian_Caryatid
(S)30 = Secondary_St. Sebastian_Pedestal base
(S)31 = Secondary_St. Sebastian_Rope
(S)32 = Secondary_Temptation_Bottom left corner plaque
(S)33 = Secondary_Temptation_Stable Monsters
(S)34 = Secondary_Temptation_Top Clouds
(S)35 = Secondary_Visit_Background
(S)36 = Secondary_Visit_Left bottom shrubs
(S)37 = Secondary_Visit_Left top palm tree fruits
(S)38 = Secondary_Visit_Right bottom plants/Coat of arms
(S)39 = Secondary_Visit_Top right tree/Raven

Appendix A3

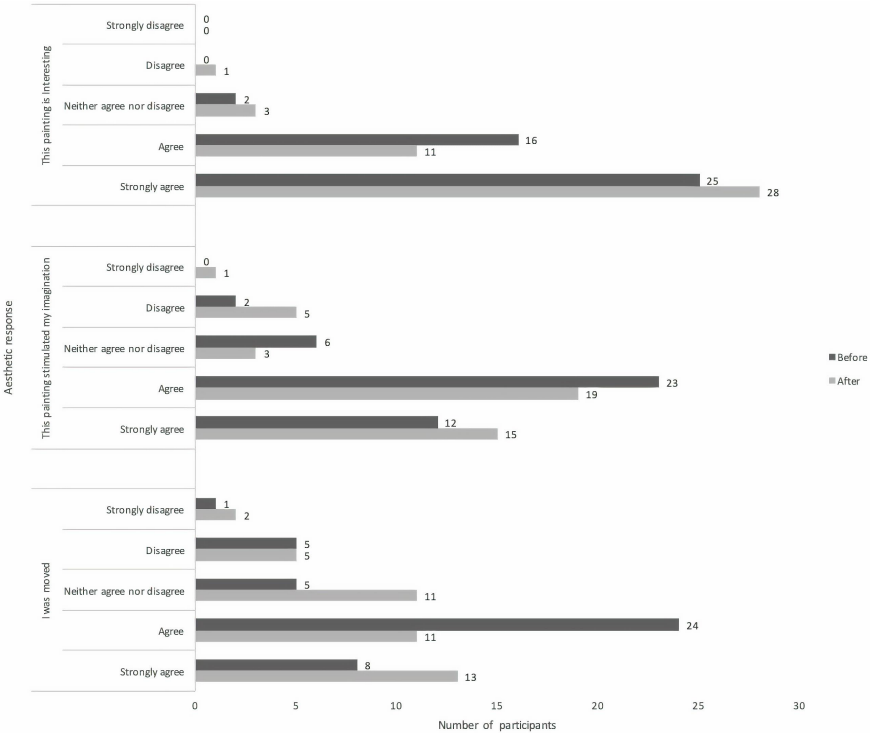

Figure A2. Answers to the questionnaire, question 1: "Classify the sentences below based on your visit. Please choose one option only" — aesthetic responses.