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How realistic are painted lightnings? Quantitative comparison of the morphology of painted and real lightnings: a psychophysical approach

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Inspired by the pioneer work of the nineteenth century photographer, William Nicholson Jennings, we studied quantitatively how realistic painted lightnings are. In order to answer this question, we examined 100 paintings and 400 photographs of lightnings. We used our software package to process and evaluate the morphology of lightnings. Three morphological parameters of the main lightning branch were analysed: (i) number of branches N_b, (ii) relative length r, and (iii) number of local maxima (peaks) N_p of the turning angle distribution. We concluded: (i) Painted lightnings differ from real ones in N_b and N_p. (ii) The r-values of painted and real lightnings vary in the same range. (iii) 67 and 22% of the studied painted and real lightnings were non-bifurcating ($N_b = 1$, meaning only the main branch), the maximum of N_b of painted and real lightnings is 11 and 51, respectively, and painted bifurcating lightnings possess mostly 2–4 branches, while real lightnings have mostly 2–10 branches. To understand these findings, we performed two psychophysical experiments with 10 test persons, whose task was to guess N_b on photographs of real lightnings which were flashed for short time periods $\Delta t = 0.5$, 0.75 and 1 s (characteristic to lightnings) on a monitor. We obtained that (i) test persons can estimate the number of lightning branches quite correctly if $N_b \leq 11$. (ii) If $N_b > 11$, its value is strongly underestimated with exponentially increasing difference between the

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real and estimated numbers. (iii) The estimation is independent of the flashing period Δt of lightning photos/pictures. (iv) The estimation is more accurate, if skeletonized lightning pictures are flashed, rather than real lightning photos. These findings explain why artists usually illustrate lightnings with branches not larger than 11.

1. Introduction

From times out of mind, humans record their surrounding world in the form of paintings, drawings, graphics or etchings produced on the walls of ancient caves or canvases exhibited later in art museums. Several studies have been published which analysed and criticized these artworks from the perspective of natural sciences. Zerefos *et al*. [1,2], for example, examined sunsets/sunrises in paintings. Using the red-to-green ratio as a proxy for atmospheric effects and the aerosol optical depth, they compared the reddish hue of painted and real sunsets/sunrises after major volcanic eruptions. They obtained that the red hue of painted rising/setting sun positively correlates with the increased atmospheric aerosol concentration. In their book on rainbow optics, Lee & Fraser [3] devoted a whole chapter to the critique of erroneous rainbow illustrations. Gedzelman [4], Sassen [5], Tape *et al*. [6,7], Farkas *et al*. [8] and Seidenfaden [9] analysed and interpreted old descriptions of numerous atmospheric optical phenomena (especially ice halo displays, rainbows and coronas) and noted their artistic biases resulting from prevailing styles and social or religious influences.

On their paintings, many artists—among others William Turner (1775–1851), Eugene Delacroix (1798–1863) and the contemporary Toni Grote (1960–)—have depicted one of the most spectacular atmospheric phenomena, the lightning. But before the dawn of photography, lightnings have often appeared in paintings as awkward zigzags slicing through the sky. As Nasmyth [10] suggested, these inaccuracies might have originated from the thunderbolt in Jupiter's hand as sculptured by the early Greeks. In the 1880s, the photographer of the Pennsylvania Railroad, William Nicholson Jennings (1860–1946) was motivated by the same question, whether these zigzag forms of painted lightnings do or do not correspond to the form of real lightnings, and wanted to prove this photographically [11–14]. His first attempts were unsuccessful, because his photographic plates were not sensitive enough for an extremely short lightning exposure. But later, he could successfully prove the diversity of lightning paths captured with his plate camera and never found any zigzag path. However, the very first daguerreotype of a lightning bolt was made earlier by Thomas Martin Easterly (1809–1882) on 18 June 1847 [15]. Nonetheless, Jennings is credited as taking the first photograph of lightning on 2 September 1882 [13,16]. Shortly thereafter, Jennings' photos and firsthand observations had important impacts on meteorology and natural history as many experts attempted to use them to identify different types of lightnings and point out the inaccuracies in earlier representations of thunderstorms [14].

Inspired by the pioneering work of Jennings, we studied quantitatively how realistic painted lightnings are. We examined and compared the morphology of 100 paintings and 400 photographs of real lightnings with the use of our self-developed computer software. To understand our quantitative findings, we performed psychophysical experiments with 10 test persons, whose task was to guess the number of branches of the main lightning path on photographs of real lightnings which were flashed on a monitor for short periods characteristic to lightnings.

2. Material and methods

(a) Collection of pictures of painted and real lightnings

From the Internet, we have collected 100 painted lightnings. They originated from the period 1500–2015. Unfortunately, the production years of 10 painted lightnings were unknown, but in spite of this, we found them worthwhile to analyse, as well. The source (website) and some other relevant information of these lightning depictions are given in the diploma thesis of Stromp [17]. We obtained 400 photographs of real lightnings from several amateur atmospheric optical photographers (see Acknowledgements).

(b) Quantitative study of lightning morphology on pictures

For the evaluation of pictures of painted and real lightnings, we used the software AlgoNet (http://www.estrato.hu/algonet) that is a framework for simple handling of image processing algorithms. First, all investigated lightning pictures were scaled to be 1000 pixels wide so that they become comparable with each other for various measures to be calculated later. Then, black-and-white binary images of the main and lateral lightning branches were created. In these images, the pixels of the background and the lightning have the value of 0 (black) and 1 (white), respectively. To create the binary image of the straight line from the starting point to the end point of the main lightning branch, we drew manually a straight line between these two points.

To determine the main lightning branch, we took the green colour channel of the picture, because the image quality was the best in the green due to the structure of the Bayer-filter of imaging sensors where there were twice as many green pixels as red or blue ones. First, we thresholded the image. This procedure highlighted the brightest pixels, filtered out the majority of the lateral branches and kept the majority of the main branch. Then, a morphological dilation was performed with a circular kernel, so that the gaps along the main branch were filled. We thinned the main branch by performing a 4-connected skeletonization [18]. We checked the binary image of the main branch which was overpainted on the original photo and corrected manually any misdetections of the branch points.

To determine/recognize the lateral lightning branches, we again used only the green channel of the colour picture. The green picture was noise-filtered with a narrow and a wide Gaussian function, then the latter filtered picture was divided by the former one, i.e. every pixel-value of the latter picture was divided by the corresponding pixel-value of the former one. The reason for this was that the bright main lightning branch was usually overexposed and had a surrounding halo with a gradual intensity decrease, as a consequence of which the wide Gaussian filter did not change its appearance considerably, whereas the lateral branches were thinner without a halo, thus the wide Gaussian filter decreased their intensities significantly. After dividing the two images, the intensities of the main branch differed considerably from those of the lateral branches. Next, we thresholded the obtained picture, which resulted in a binary image of the lateral branches, which were then thinned by using a 4-connected skeletonization. Finally, we checked the binary image of the lateral branches which were overpainted on the original photo and corrected any misdetection of the lateral branches.

To characterize the lightning morphology, we calculated the following three measures of the main lightning branch from the obtained binary (black = background, white = recognized lightning) image:

(1) Relative length $r = q/Q$, where q is the distance (in pixels) between the start and end points of the main branch, and Q is the length of the main branch (all pixels belonging to the main branch, figure 1*a*). q and Q were obtained by counting the corresponding white pixels on the binary image.

(2) Number of branches N_b. For this, the binary image of the lateral branches was thinned with an 8-connected skeletonization. Considering the eight neighbouring pixels of each pixel of this thinned image, the followings were true: (i) In the end point of a branch the image had one neighbouring white pixel. (ii) In a non-bifurcating section of a branch a white pixel had two neighbouring white pixels. (iii) In a bifurcation a white pixel had more than two neighbouring white pixels. (iv) A background black pixel could have 0–8 neighbouring white pixels. Based on these properties, a linear filtering of the thinned binary image was performed with a 3×3 kernel weighted by a value of 10 in its central

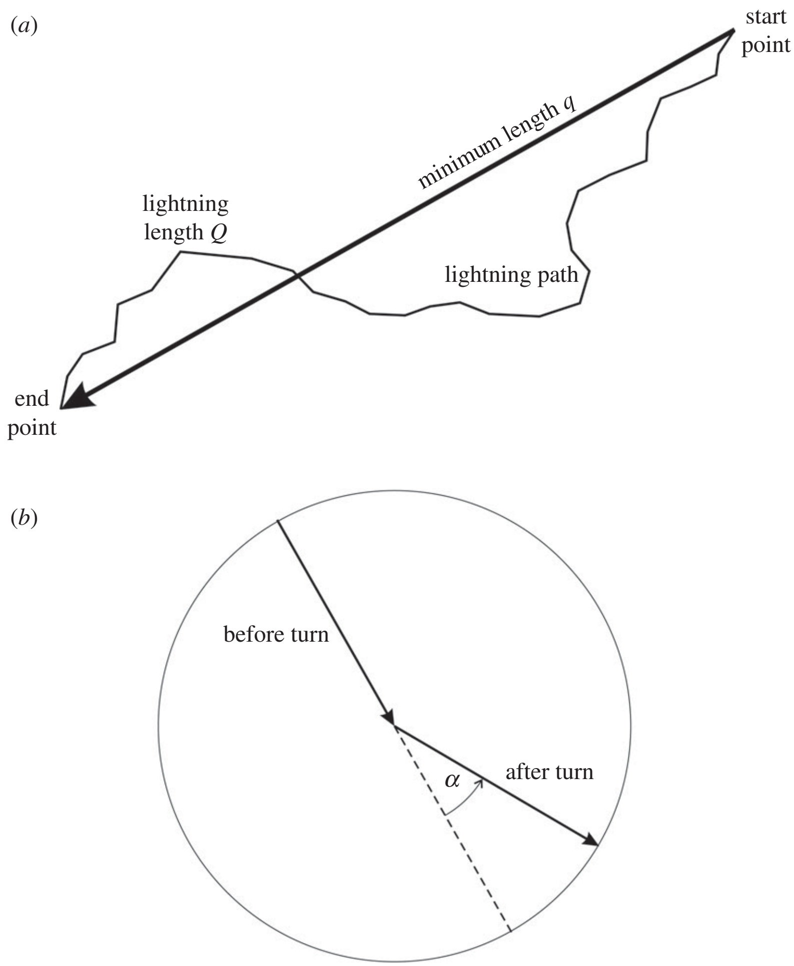

Figure 1. (*a*) Definition of the minimum length q and real length Q of a lightning between its start point and end point. The relative length is $r = q/Q$. (*b*) Definition of the turning angle α of a lightning path/branch.

anchor point and a value of 1 in the 8 border points. This kernel-filtering resulted in an image, where the pixel weights were 0–8 in the background, 11 at the end points of branches, 12 in the non-bifurcating branch sections, and >12 at bifurcations. After thresholding this image, we got a binary image, where only the points of bifurcations had non-null weights. Note that after this processing a bifurcation could have more than one non-null weighted pixel. Thus, instead of simply counting the pixels with non-null weights, we calculated the number of connected components of non-null weighted pixels on this binary image. This gave the number of branches N_b of the main lightning branch.

(3) Finally, we studied the zigzagness of the main lightning branch, i.e. we calculated the number of branch pixels having a given turning angle α (figure 1*b*). For this the binary image of the main lightning branch was thinned by using a 4-connected skeletonization. We calculated α for each pixel of the main branch by the SLOW corner detection algorithm, which is a highly unoptimized generalization of the FAST (Features from Accelerated Segment Test) corner detection algorithm [19]. We defined an 8-connected circle (i.e. the adjacent pixels of its outline are connected with either their corners or their edges), with a given radius around the investigated branch pixel, and calculated the number of adjacent null-weighted pixels along the circle outline. This number was

proportional to the turning angle α of the branch at the investigated pixel. The resolution of α increases with increasing circle radius. However, the use of larger radii had the disadvantage that the turns within the circle were hidden. Thus, we used an optimized radius of five pixels.

(c) Psychophysical experiments: guessing the number of branches of real lightnings

In a darkened laboratory, we performed two psychophysical experiments with 10 test persons (aged between 20 and 53 years). Although country residents may be keener observers of lightnings than city folk, all test persons lived in cities. Their task was to guess the number of branches N_b on pictures of real lightnings which were flashed on a monitor for short time periods typical for lightnings.

(i) Experiment 1

In this experiment, colour photographs of 60 different real lightnings were presented on a computer monitor. Each photo was shown three times for $\Delta t = 0.5$, 0.75 and 1 s. With this we simulated the short (less than 1 s) period Δt of the flash of lightnings. The vast majority of lightnings are not longer than about 1 s [20,21]. The test person said the recognized number of branches N_b of the seen lightning to the experiment leader, then pressed a keyboard button to see the next photo. Hence, the showing of flashes was controlled by the test persons themselves. The flashes with randomly changing durations Δt ($= 0.5$, 0.75, 1 s) were thus displayed after one another in every 3–5 s. In an experiment session, the 60 different lightning photos with three different Δt-values were shown in a randomized order. Thus, in a session a test person was confronted with $60 \times 3 = 180$ lightning photos, on which N_b had to be guessed.

(ii) Experiment 2

In this experiment, black-backgrounded pictures of the white skeletons (graphs with a thickness of 1 pixel) of 60 different real lightnings were presented on a computer monitor. In experiment 1 the problem was that on a given photo the test person first (i) had to visually find the site of a lightning in the often structured background composed of clouds, trees/bushes and buildings, and then (ii) had to guess N_b. Task (i) needed a considerable part of the available short period Δt, and therefore did not leave enough time for task (ii). The purpose of experiment 2 was to eliminate this problem and to imitate better real lightning flashes: In experiment 2, the background was homogeneous black, thus the white lightning skeleton (graph) could be easily and promptly recognized, thus N_b could be guessed more easily. Other details of experiment 2 were the same as those of experiment 1.

Each experiment was conducted five times with 10 test persons on five different days per person. The lightning pictures were presented in a random order.

(d) Statistics

For the comparison of the measured data, we calculated comparative errors or used t-test with the statistical software package R.

3. Results

(a) Number of branches of the main lightning path

According to figures 2–5, in the number of branches N_b of the main lightning path, painted and real lightnings do not separate from each other: the former are a subset of the latter. However, the maximum of N_b of the studied painted lightnings is only 11, while the investigated real lightnings have a maximum of 51 branches. There are many non-bifurcating painted ($67/100 = 67\%$) and

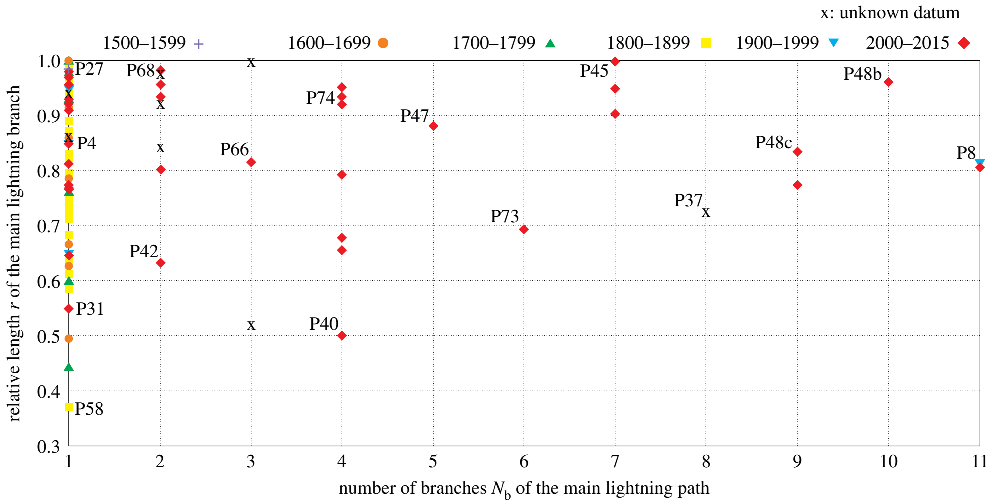

Figure 2. Relative length r of the main branch of 100 painted lightnings as a function of the number of branches N_b of the main lightning path, where the different symbols mean different centuries. x: painted lightnings with unknown year of production. The pictures of painted lightnings marked with different P-numbers can be seen in figure 3. (Online version in colour.)

real ($93/400 = 22.25\%$) lightnings. If painters display a bifurcating lightning, it has mostly 2 ($11/100 = 11\%$) or 4 ($8/100 = 8\%$) branches. Real lightnings have mostly 5 ($28/400 = 7\%$) or 3 ($27/400 = 6.75\%$) branches. In average, painted and real lightnings possess 2.2 and 8.4 branches, respectively.

It is clear from figure 6 that bifurcating painted lightnings existed already before 1882, when William Nicholson Jennings took his first photos about bifurcating lightnings. However, after 1882 more (23) bifurcating lightnings were painted than earlier (10) (figure 6). Since 2000, the number of painted lightnings with more than one branch has drastically increased (figure 6), in all probability due to the rapid spread of digital photographic cameras.

(b) Relative length of the main lightning branch

According to figures 2 and 4, apart from a few lightnings, the relative length r of the main branch of painted and real lightnings ranges between 0.6 and 1. The average r-value of painted and real lightnings is 0.83 and 0.88, respectively. In figure 7 we can see that r_{average} of painted lightnings (averaged for a temporally continuously shifting 100-year period) changes between 0.73 and 0.92. Before and after 1882, r_{average} varies around 0.81 and 0.84, respectively.

(c) Zigzagness (local turning) of the main lightning branch

We can see in figure 8 that the distribution of the turning angle α of the main lightning branch has 1, 2, 3 or 4 peaks (local maxima) at $\alpha_{\text{peak}} \neq 0$ around $\alpha_{\text{min}} = 0°$ (meaning no turn) and 1 local minimum at $\alpha_{\text{min}} = 0°$. If $\alpha_{\text{peak}} > 0°$ or $\alpha_{\text{peak}} < 0°$, then the lightning branch tendentiously turns leftward or rightward, respectively (figure 1*b*). Among the 100–100 selected real and painted lightnings there are more (27%) 1-peaked real lightnings than painted ones (17%), which is a statistically not significant difference, because CE > DIFF (comparative error: CE = 11.4, difference: DIFF = 10). On the other hand, there are more (75%) 2-peaked painted lightnings than real ones (68%), which is again a statistically not significant difference (since CE = 12.47 > DIFF = 7). Furthermore, only a very few painted ($6 + 2 = 8\%$) and real ($3 + 2 = 5\%$) lightnings with three or four peaks occur. Among the 100–100 selected painted-real lightnings, $100 - 17 = 83$ painted and $100 - 27 = 73$ real lightnings had a local minimum at $\alpha = 0°$. The main

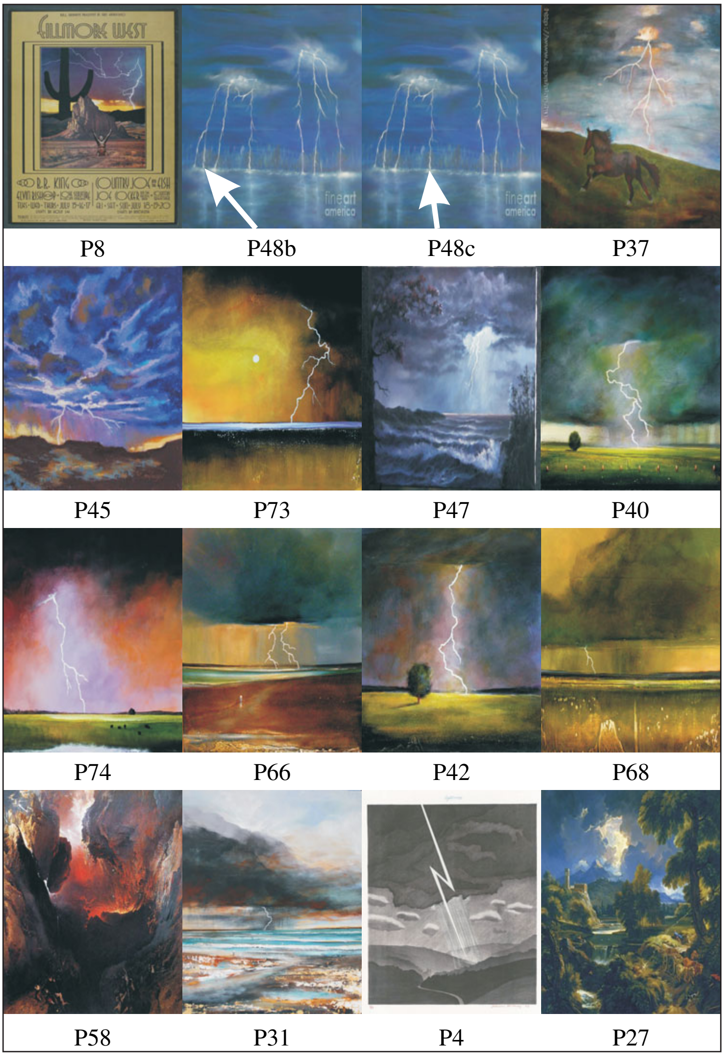

Figure 3. Pictures of painted lightnings marked with P-numbers in figure 2. (Online version in colour.)

branch of these lightnings is nearly straight, that is, the numbers of local left ($\alpha > 0°$) and right ($\alpha < 0°$) turns with equal turning angles $|\alpha|$ are the same.

(d) Guessed number of branches of real lightnings

Figure 9 shows the difference $\Delta N = N_e - N_b$ and the standard deviation σ of N_e as a function of the number of branches N_b of real lightnings when the lightning photos/pictures were flashed for $\Delta t = 0.5$, 0.75 and 1 s, where N_e is the mean of the estimated number of branches averaged for 10 test persons for real lightning photos and skeletonized pictures of real lightnings. If $N_b \leq 11$, then N_b was slightly overestimated ($\Delta N > 0$, $N_e > N_b$), but this overestimation is not significant. On the other hand, if $N_b > 11$, then N_b was tendentiously underestimated ($\Delta N < 0$, $N_e < N_b$) and this underestimation increases rapidly (exponentially) with increasing N_b for both the real and skeletonized lightning pictures flashed. This underestimation is significant for $N_b > 30$. According to table 1, for skeletonized lightning pictures the average standard deviations σ (4.53–4.74) are statistically significantly smaller (according to t-test for $\Delta t = 0.5$ s: t-value $= 3.224$, $p = 0.0008 < 0.05$ significant; for $\Delta t = 0.75$ s: t-value $= 2.812$, $p = 0.0028 < 0.05$ significant; for

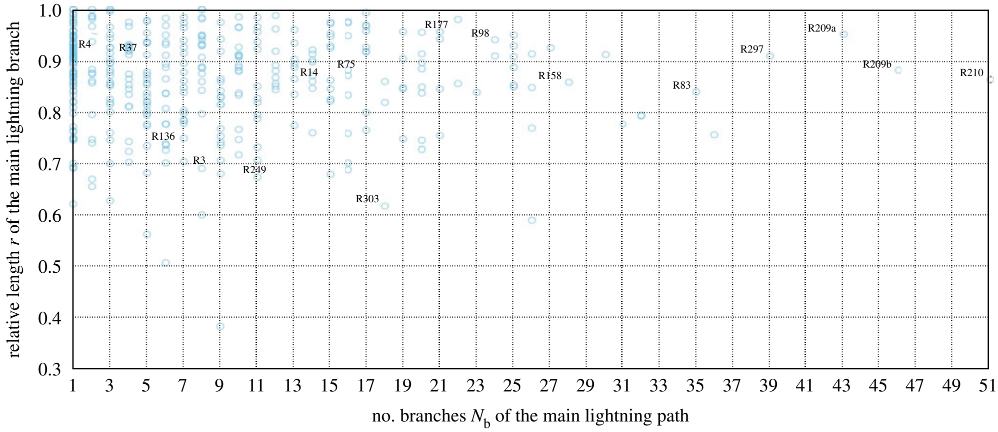

Figure 4. Relative length r of the main branch of 400 real lightnings as a function of the number of branches N_b of the main lightning path. The pictures of real lightnings marked with different R-numbers can be seen in figure 5. (Online version in colour.)

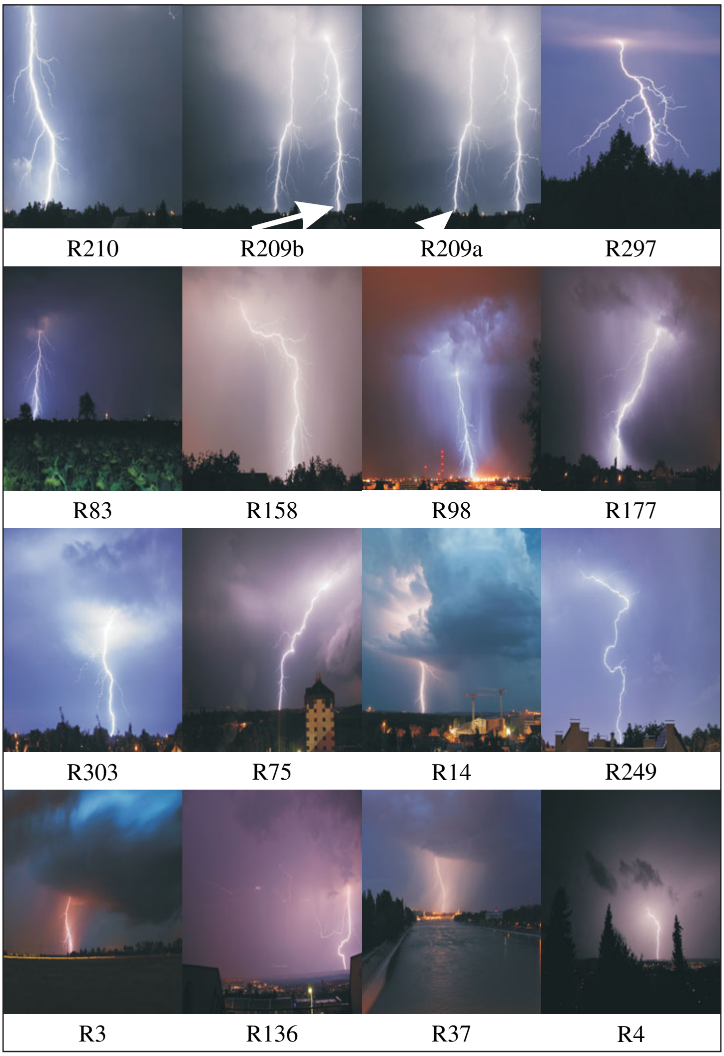

Figure 5. Pictures of real lightnings marked with R-numbers in figure 4. (Online version in colour.)

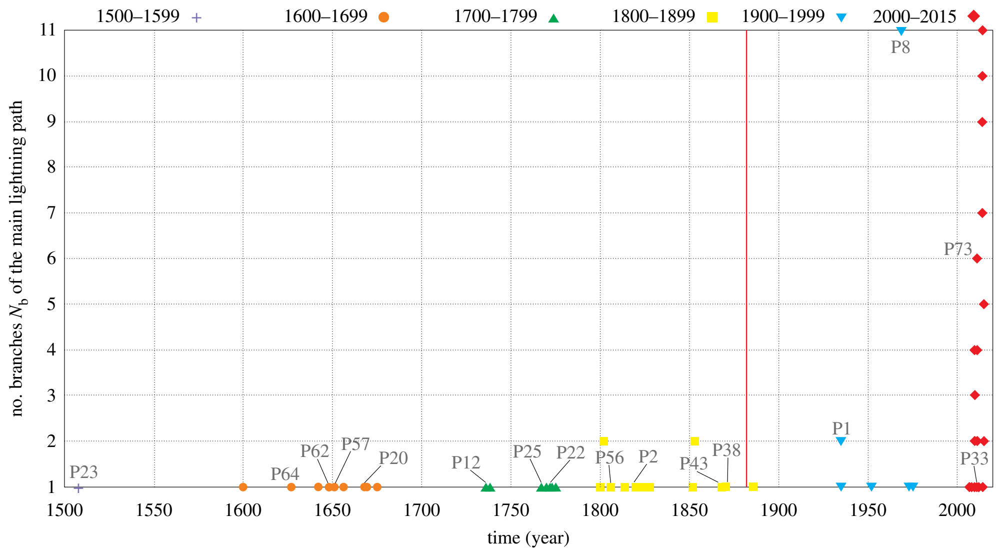

Figure 6. Number of branches N_b of 100 painted lightnings as a function of time. Different symbols mean different centuries. The vertical line marks 1882, when William Nicholson Jennings took his first photographs about lightnings. (Online version in colour.)

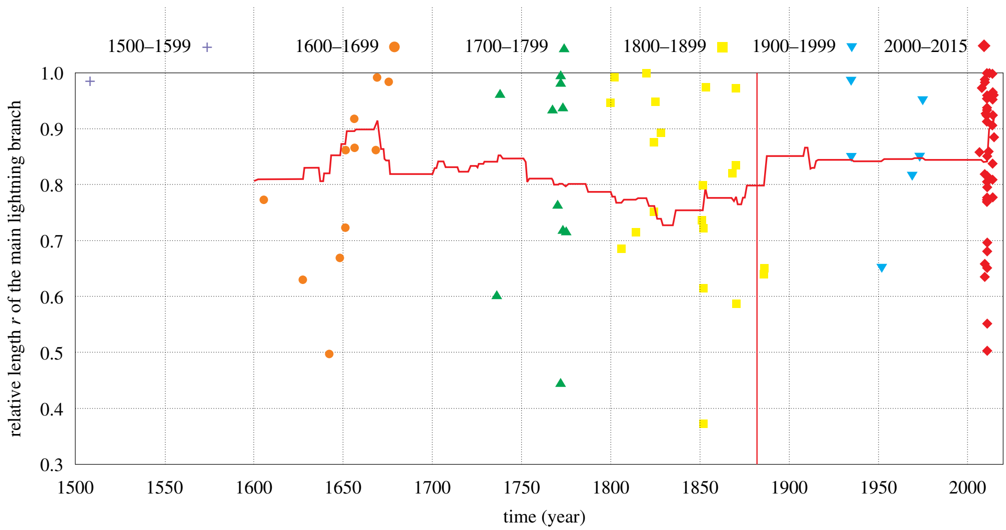

Figure 7. Relative length r of the main branch of 100 painted lightnings as a function of time. The continuous curve shows the r-value averaged for a temporally continuously shifting 100-year period. Different symbols mean different centuries. The vertical line marks 1882, when William Nicholson Jennings took his first photographs about lightnings. (Online version in colour.)

$\Delta t = 1$ s: t-value $= 3.331$, $p = 0006 < 0.05$ significant) than for real lightning photos (6.22–6.46). Furthermore, the averages of ΔN are statistically not significant between skeletonized and real lightning pictures/photos (according to t-test for $\Delta t = 0.5$ s: t-value $= -0.0707$, $p = 0.4718 > 0.05$ not significant; for $\Delta t = 0.75$ s: t-value $= -0.3216$, $p = 0.3741 > 0.05$ not significant; for $\Delta t = 1$ s: t-value $= -0.0031$, $p = 0.4987 > 0.05$ not significant). From these we conclude the following:

(a) If the number of lightning branches was not larger than 11, then test persons could estimate it quite correctly.

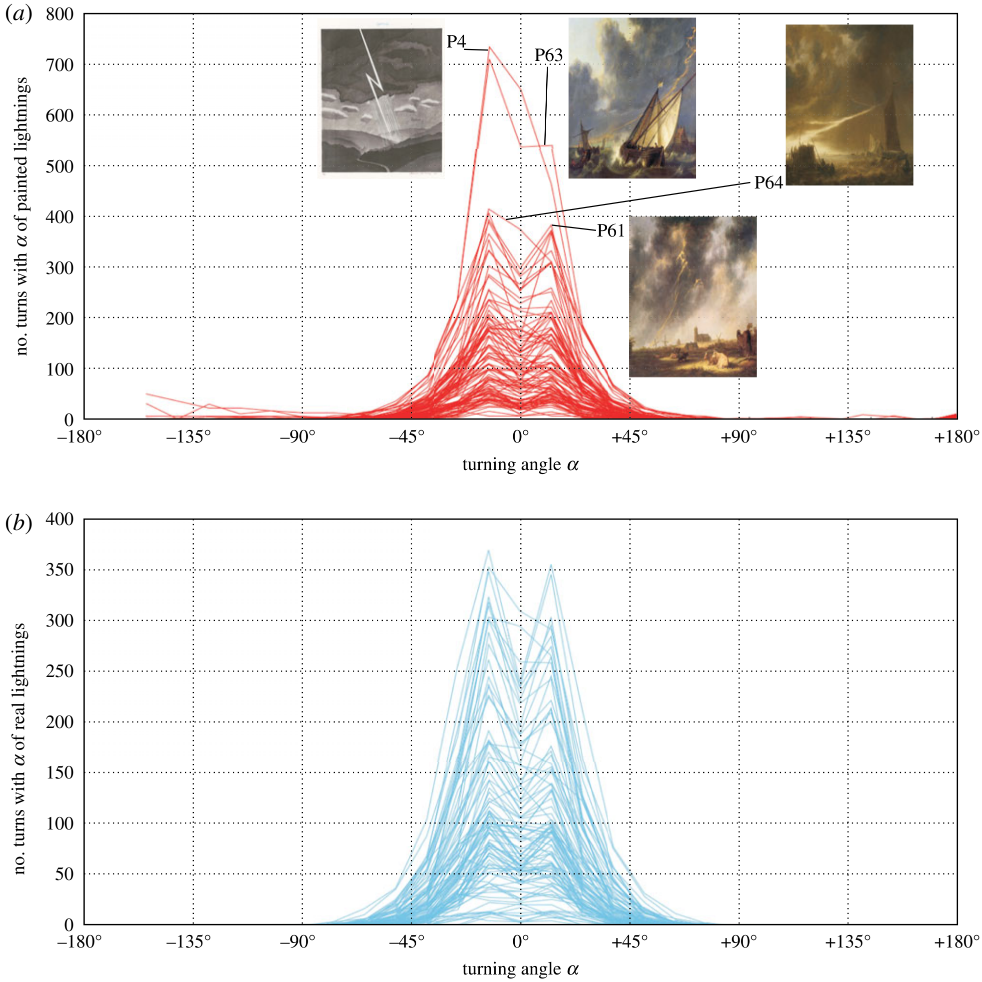

Figure 8. Distribution of the turning angle α of the main branch of 100 painted (*a*) and 100 randomly selected real (*b*) lightnings, where $\alpha = 0°$ means no turn, $\alpha > 0°$ and $\alpha < 0°$ mean left and right turns, respectively (figure 1*b*). (Online version in colour.)

(b) If the number of lightning branches was larger than 11, test persons strongly underestimated it with exponentially increasing absolute difference between the real and estimated numbers.
(c) The estimation of the number of lightning branches was independent of the flashing period Δt ($=0.5, 0.75, 1$ s) of lightning photos/pictures.
(d) The estimation of the number of lightning branches was more accurate, if test persons were confronted with skeletonized lightning pictures, rather than with real lightning photos.

4. Discussion

As we mentioned in the Introduction, scientists sometimes feel a need to analyse and criticize artistic illustrations (e.g. drawings, paintings) from the perspective of natural science. Fikke *et al.* [22], for instance, suggested that in the background of the famous painting 'The Scream' produced in 1893 by Edward Munch (1863–1944) polar stratospheric clouds could be illustrated, rather

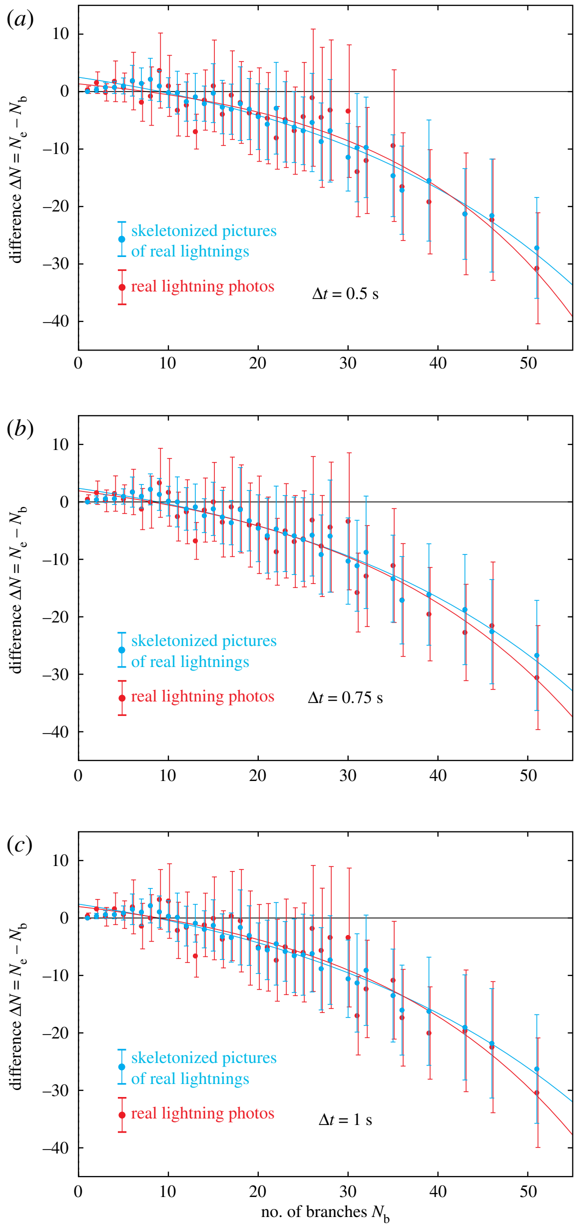

Figure 9. Difference $\Delta N = N_e - N_b$ (dots) as a function of the number of branches N_b of real lightnings, if the lightning photos/images were flashed for $\Delta t = 0.5$ s (*a*), 0.75 s (*b*) and 1 s (*c*), where N_e is the mean of the estimated number of branches averaged for 10 test persons. Vertical I-shaped bars show the standard deviation σ of N_e. Black: real lightning photos. Grey: skeletonized pictures of real lightnings. (Online version in colour.)

than a volcanic sunset as believed earlier [23]. Merriam *et al*. [24] analysed numerous paintings about landscapes of the North-American Kansas from a geographical and geological perspective. Horváth *et al*. [25,26] studied prehistoric and modern depictions of walking quadruped animals (mainly horses) on 1307 paintings, graphics, statues, postal stamps, reliefs and prehistoric cave arts from a biomechanical perspective, and found that cavemen illustrated quadruped walking more precisely than later artists. Thornes [27] illustrated how the paintings of John Constable (1776–1837), Claude Monet (1840–1926) and Olafur Eliasson (1967–) could help providing

Table 1. Average $\langle \Delta N\rangle = (1/n)\sum_{i=1}^{n} \Delta N_i$ of the difference $\Delta N = N_e - N_b$ and average $\langle\sigma\rangle = (1/n)\sum_{i=1}^{n}\sigma_i$ of the standard deviation σ versus the flashing period $\Delta t = 0.5$, 0.75 and 1 s measured for photos of real lightnings and skeletonized pictures of real lightnings, where N_b is the number of branches of real lightnings, N_e is the mean of the estimated number of branches averaged for 10 test persons, and $n = 60$ is the number of measurements for a given Δt.

	photos of real lightnings			skeletonized pictures of real lightnings		
flashing period Δt (s)	0.5	0.75	1	0.5	0.75	1
$\langle \Delta N\rangle$	−4.17	−4.46	−4.15	−4.09	−4.09	−4.14
$\langle\sigma\rangle$	6.46	6.22	6.31	4.70	4.74	4.53

effective representations of atmosphere, weather and climate involving public participation and understanding. Tape *et al*. [6,7] exemplified that famous medieval diagrams of ice crystal halos occasionally led to scientific debates about the possible existence of unusual shaped, e.g. cubic ice crystals in the atmosphere [28–30] and about the possibility of the illustrated but uncertain phenomena (e.g. Scheiner's 28° circular halo from the 1629 Rome halo display and the still mysterious 90° Hevel's halo from the 1661 Danzig display). These drawings and paintings could also be realistic and prove to be the first observations of an extraordinary atmospheric phenomenon. For example, Parry arc was named after the famous polar explorer William Edward Parry (1790–1855), who first described this rare halo on 8 April 1820 when his ships became trapped in the ice during the expedition to find the North West Passage [31,32]. The two earliest observations of polar stratospheric clouds are also known from paintings and diary recordings from 1901 by the Danish artist, Aksel Jørgensen (1883–1957) and from 1903 by the scientist-artist member of Scott's Antarctic expeditions, Edward Adrian Wilson (1872–1912) [33,34].

In this work, we compared quantitatively the morphology of painted and real lightnings in order to reveal how realistic painted lightnings are. This question had been raised by J. Nasmyth in 1857 and W. N. Jennings in the 1880s for the first time. Painters may illustrate lightnings most frequently in their studio from memory, rather than in the open air immediately after their observation of a lightning during a thunderstorm. This could be one of the reasons for the difference between certain morphological characteristics of painted and real lightnings. Painters may illustrate lightnings nowadays from captured photos in addition to memory immediately or well after the event. This may influence the increase in branching seen after 2000. We investigated quantitatively three characteristics, namely the number of branches N_b, relative length r, and zigzagness of the main lightning branch. According to our comparison, the main difference between painted and real lightnings is in N_b: although 67 and 22% of painted and real lightnings, respectively, are non-bifurcating ($N_b = 1$), the maximum of N_b of the studied painted and real lightnings is 11 and 51, respectively, and painted bifurcating lightnings have mostly 2–4 branches, while real lightnings have mostly 2–10 branches.

In order to understand the possible reasons for these differences, we performed psychophysical laboratory experiments, from which we learned that artists paint maximally 11 branches of lightnings, because humans (test persons) could correctly estimate this number only if the number of lightning branches is not larger than 11. If the number of lightning branches is larger than 11, humans cannot count the lateral branches during the short visibility period ($\leq$1 s) of lightnings. Consequently, humans progressively underestimate the number of lateral branches of lightnings with increasing branch number. If a human sees a bifurcating lightning, she/he can promptly distinguish and count the lateral branches if their number is not larger than 10. It is well known that there are three main different enumeration processes in humans: (i) *subitizing*—when the number of items (e.g. dots, bars, apples, etc.) is between 1 and 5, (ii) *counting*—when the number of items ranges from 6 to 10, and (iii) *estimation*—when the number of items is more than 10 [35]. Humans show a gradual decline in the accuracy of enumeration as the number of items increases [36].

According to the results of our psychophysical experiments, if the flashing period Δt is 0.5 s, the counting of lightning branches is correctly performed up to 11 branches and a longer period is not necessary to count correctly the branches. Above 11 branches even the maximal visibility time (1 s) is too short to count or estimate the branches correctly. This is the likely reason for our finding that the estimation of N_b is independent of the flashing period Δt (=0.5, 0.75, 1 s) of lightning photos or pictures.

The only relevant difference between the perception of real lightning photos and skeletonized lightning pictures is that the estimation of the number of lightning branches is more accurate if the test persons are confronted with skeletonized lightning pictures. This can be explained in the following way: On a given lightning photo, the observer first had to find the lightning itself in the frequently structured background, and only then could the number of lightning branches be guessed. The finding of lightning needed a short period τ, and the branch counting could be done only during the remaining $\Delta t - \tau$ period. When skeletonized lightning pictures were presented to the test persons, they could perceive promptly ($\tau \ll 1$s) the white lightning skeleton (graph) in the black background, and thus enough time $\Delta t - \tau$ remained for branch counting. Since $\tau_{\text{skeletonized}} < \tau_{\text{real}}$, it is understandable that the estimation of the number of branches was more accurate for skeletonized lightning pictures than for real lightning photos.

When artists paint lightnings, in principle they participate in a special psychophysical experiment, the results of which are the painted lightnings. From the morphology of these lightnings one can conclude, how accurately the human visual system is able to perceive, process and extract the relevant morphological information from a lightning flashing not longer than about 1 s. The most important difference between this 'artistic psychophysical experiment' with painters and our experiment is that the painters have mostly fixed the seen lightning on their canvas in a long period after the lightning flash, while in our experiment the test persons communicated the number of lightning branches immediately after a lightning flashed on the monitor. Obviously, the memory plays an important role in the creation of lightning paintings. Lightning painting could have been mimicked even better in such an experiment, if the test persons had been asked about the number of branches of the seen lightning several days after seeing the flash of a lightning picture on the monitor. However, such an experiment would be enormously time-consuming.

A further reason for the fact that people usually remember only a maximum of 11 lightning branches could be simply the visibility of these branches: they are usually not only thinner than the main lightning branch, but also less bright and thus less visible and obvious. A camera (digital or conventional) can make the branches appear far more prominently than what the human eye perceives and the memory remembers. The maximum number of branches of 51 found for real lightnings in our study is surely underestimated, because cameras cannot register/detect branches that are too dim to show up in photographs.

In our second psychophysical experiment, due to displaying lightning skeletons we showed black-and-white images for the test persons, and therefore different hues, shades and colorations, that painters might have used, were ignored. This is, however, not a problem, because real lightnings are usually not or only slightly coloured.

Different painters might have painted the lightnings at different distances. Similarly, the real lightnings used in our two psychophysical experiments were also photographed from various (unknown) distances.

At geographically different regions the morphology of lightnings may be more or less different. Morphological differences are imaginable between lightnings over the following different regions, for example: (i) tropical versus temperate zone, (ii) forests versus treeless savannahs versus huge water surfaces (rivers, lakes, oceans), (iii) high mountains versus low altitude plains. Since meteorological/geographical data about the regionality of lightning morphology were not available for us, this issue was not considered in our study. Even if we found such regional lightning data, this information would be unusable, because it is generally impossible to know where the painters had seen their lightnings and then remembered them to put on the canvas. But we admit that the regionality of lightning morphology (if existed) could have had an influence on the ways painters remembered the shapes of lightnings.

It is unknown, how realistically the artists of paintings, studied in this work, wanted to illustrate the mentioned three morphological characteristics of lightnings. One would assume that a painted lightning with one or more atypical characteristics (i.e. with parameter-values considerably differing from those of real lightnings) is the result of the artist's freedom or her/his incorrect observation and/or bad memory. Usually, it is impossible to ascertain which options are true, thus this is out of the scope of our present study.

However, there were surely numerous artists about whom we can suspect that they aimed to paint lightnings and many other features and objects of their visual environment as realistically as possible. We can mention Joseph Mallord William Turner (1775–1851), the famous English romantic landscape (plain air style) painter, for example, who in his younger years has illustrated the guidebooks of the dawning English tourism with wonderful panorama pictures of landscapes and cities. After such a past, he understandably became one of the most typical representatives of realistic painting. His main characteristic was that what he saw in reality, he translated to his own romantic style and painted that on the canvas (https://en.wikipedia.org/wiki/J._M._W._Turner). We studied also three painted lightnings produced by Turner. The characteristics of these lightnings are typical, that is they are similar to real lightnings.

Many atmospheric electric discharges are cloud-cloud or cloud lightning between two clouds or in one cloud [20,21]. These lightnings are more or less tilted or nearly horizontal and do not reach the ground. In our study we did not consider such lightnings, that did not occur in the investigated paintings. The most atypical shape of painted lightnings is the schematized zigzag-S (see painting P4 in figure 3) being wide spread in everyday life: such a shape occurred on the shield of Roman soldiers, for instance, and occurs as a symbol of electricity (e.g. dangerous high voltage) nowadays. William Nicholson Jennings has shown that such a zigzag-S-shaped lightning does not exist in reality.

Ethics. For our studies no permission, licence or approval was necessary.

Data accessibility. Our paper has no electronic supplementary material.

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References

1. Zerefos CS, Gerogiannis VT, Balis D, Zerefos SC, Kazantzidis A. 2007 Atmospheric effects of volcanic eruptions as seen by famous artists and depicted in their paintings. *ASTM Spec. Tech. Publ.* **7**, 4027–4042. (doi:10.5194/acp-7-4027-2007)
2. Zerefos CS *et al.* 2014 Further evidence of important environmental information content in red-to-green ratios as depicted in paintings by great masters. *ASTM Spec. Tech. Publ.* **14**, 2987–3015. (doi:10.5194/acp-14-2987-2014)
3. Lee Jr RL, Fraser AB. 2001 *The rainbow bridge: rainbows in art, myth, and science*. Washington, DC: Penn State University Press.
4. Gedzelman SD. 1991 Atmospheric optics in art. *Appl. Opt.* **30**, 3514–3522. (doi:10.1364/AO.30.003514)
5. Sassan K. 1994 Possible halo depictions in the prehistoric rock art of Utah. *Appl. Opt.* **33**, 4756–4760. (doi:10.1364/AO.33.004756)

6. Tape W. 1994 *Atmospheric halos*. Antarctic Research Series, vol. 64. Washington, DC: American Geophysical Union.
7. Tape W, Seidenfaden E, Können GP. 2008 The legendary Rome halo displays. *Appl. Opt.* **47**, H72–H84. (doi:10.1364/AO.47.000H72)
8. Farkas A, Kiricsi Á, Klemm L. 2011 Old halo descriptions from the 17–18th century in the Hungarian National Museum. *Fizikai Szemle* **61**, 407–413. (in Hungarian).
9. Seidenfaden E. 2011 Found: a diagram of the 1630 Rome halo displays. *Appl. Opt.* **50**, F60–F63. (doi:10.1364/AO.50.000F60)
10. Nasmyth J. 1857 On the form of lightning. In *Report of the Twenty-Sixth Meeting of the British Association for the Advancement of Science, Chelteham, UK, August*, pp. 1–10. London UK: James Murray.
11. Committee on Science and the Arts Report No. 2914. 1929 Investigating The Work of Mr. William N. Jennings, of Philadelphia, Pennsylvania, in the Photography of Flashes of Lightning. The Franklin Institute of the State of Pennsylvania. See https://www.fi.edu/sites/default/files/WilliamJennings_CaseFilesReport_TheFranklinInstitute.pdf (accessed 3 November 2017).
12. Silcox HC. 1993 *Jennings' Philadelphia: the life of Philadelphia photographer William Nicholson Jennings* (*1860–1946*). Philadelphia, PA: Brigton Press.
13. Hannavy J (ed.) 2008 *Encyclopedia of nineteenth-century photography*, vol. 1. Routledge, Taylor and Francis Group, New York, USA.
14. Igoe L. 2016 Capturing 'Jove's Autograph': late nineteenth-century lightning photography and electrical agency. *Panorama: J. Assoc. Hist. Am. Art* **2**, 14.
15. Palmquist PE, Kalibourn TR. 2005 *Pioneer photographers from the Mississippi to the continental divide. A biographical dictionary 1839–1865*. Stanford, CA: Stanford University Press.
16. Jennings WN. 1885 Lightning photography. *Sci. Am.* **53**, 149.
17. Stromp M. 2017 *Quantitative study of the lightning morphology in paintings*. M.Sc. diploma work, Environmental Optics Laboratory, Department of Biological Physics, ELTE Eötvös Loránd University, Budapest, Hungary, p. 74 (in Hungarian)
18. Zhang TY, Suen CY. 1984 A fast parallel algorithm for thinning digital patterns. *Commun. Assoc. Comput. Mach.* **27**, 236–239. (doi:10.1145/357994.358023)
19. Rosten E, Drummond T. 2006 Machine learning for high-speed corner detection. *Comput. Vis. ECCV* **2006**, 430–443.
20. Newcott WR, Menzel P. 1993 Lightning: nature's high-voltage spectacle. *Nat. Geogr.* **184**, 80–103.
21. Rakov V, Umann M. 2003 *Lightning physics and effects*. Cambridge, UK: Cambridge University Press.
22. Fikke S, Kristjánsson JE, Nordli O. 2017 Screaming clouds. *Geophysical Research Abstracts* 19. EGU2017-16489 (http://meetingorganizer.copernicus.org/EGU2017/EGU2017-16489.pdf)
23. Olson DW, Doescher RL, Olson MS. 2004 When the sky ran red: the story behind the scream. *Sky Telescope* **107**, 28–35.
24. Merriam DF, Charlton JR, Hambleton WW. 2006 *Kansas geology as landscape art: interpretation of geology from artistic works*. Kansas Geological Survey, Open-File Report 2006-11, 19 p.
25. Horváth G, Csapó A, Nyeste A, Gerics B, Csorba G, Kriska G. 2009 Erroneous quadruped walking depictions in natural history museums. *Curr. Biol.* **19**, R61–R62. (doi:10.1016/j.cub.2008.12.011)
26. Horváth G, Farkas E, Boncz I, Blahó M, Kriska G. 2012 Cavemen were better at depicting quadruped walking than modern artists: erroneous walking illustrations in the fine arts from prehistory to today. *PLoS ONE* **7**, e49786. (doi:10.1371/journal.pone.0049786)
27. Thornes EJ. 2008 Cultural climatology and the representation of sky, atmosphere, weather and climate in selected art works of Constable, Monet and Eliasson. *Geoforum* **39**, 570–580. (doi:10.1016/j.geoforum.2006.10.015)
28. Whalley E. 1981 Scheiner's halo: Evidence for ice *Ic* in the atmosphere. *Science* **211**, 389–390. (doi:10.1126/science.211.4480.389)
29. Weinheimer AJ, Knight CA. 1987 Scheiner's Halo: cubic ice or polycrystalline hexagonal ice? *J. Atmos. Sci.* **44**, 3304–3308. (doi:10.1175/1520-0469(1987)044<3304:SHCIOP>2.0.CO;2)
30. Riikonen M, Sillanpää M, Virta L, Sullivan D, Moilanen J, Luukkonen I. 2000 Halo observations provide evidence of airborne cubic ice in the Earth's atmosphere. *Appl. Opt.* **39**, 6080–6085 . (doi:10.1364/AO.39.006080)

31. Parry WE. 1821 *Journal of a voyage for the discovery of a north-west passage from the Atlantic to the Pacific*. London, UK: John Murray.
32. Craciun A. 2011 What is an explorer? *Eighteenth Century Stud.* **45**, 29–51. (doi:10.1353/ecs.2011.0044)
33. Legler G. 2005 *On the ice: an intimate portrait of life at McMurdo station, Antarctica*. Minneapolis, MN: Milkweed Editions.
34. Lowe D, MacKenzie AR. 2007 Review of polar stratospheric cloud microphysics and chemistry. *J. Atmos. Sol. Terr. Phys.* **70**, 13–40. (doi:10.1016/j.jastp.2007.09.011)
35. Chase WG (ed.) 1973 Visual information processes. In *Proc. Eighth Annual Carnegie Symp. on Cognition, Carnegie–Mellon University, Pittsburgh, PA, 19 May 1972*. New York, NY: Academic Press.
36. Tomonaga M, Matsuzawa T. 2002 Enumeration of briefly presented items by the chimpanzee (*Pan troglodytes*) and humans (*Homo sapiens*). *Anim. Learn. Behav.* **30**, 143–157. (doi:10.3758/BF03192916)