list of figures

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IMPRINT

SCHIAVONETTI, Luigi (1795), after a painting by Angelica KAUFFMANN (1789). *Troilus and Cressida, Act V, Scene II*. London: John & Josiah Boydell. Online: <https://commons.wikimedia.org/wiki/File:A_Scene_from_Troilus_and_Cressida_-_Angelica_Kauffmann.jpg> (Wikimedia Commons, PD).

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I DENTE, Marco (c. 1515–1527), after a drawing by Marcantonio RAIMONDI (c. 1510). *Laocoön and His Sons Being Attacked by Serpents*. Metropolitan Museum of Art, New York, 49.97.122. Online: <https://www.metmuseum.org/art/collection/search/343592> (PD).

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IV Vermeer, Johannes (1669). *The Geographer*. Städel Museum, Frankfurt am Main, 1149. Online: <https://sammlung.staedelmuseum.de/en/work/the-geographer> (PD).

V Photography of the *Baroque Library Hall*. Clementinum, Prague. Online: <https://commons.wikimedia.org/wiki/File:Clementinum_baroque_library_7.jpg> (Wikimedia Commons, CC BY-SA 4.0).

VI Ghisi, Giorgio (1530–1582), after a painting by Raphael (1509–1511). *The School of Athens*. Rijksmuseum, Amsterdam, RP-P-OB-70.601. Online: <https://www.rijksmuseum.nl/en/collection/RP-P-OB-70.601> (PD).

VII Wolff, Paul (1936–1938). *Adam Opel AG, Rüsselsheim: Produktionshalle mit Presswerk*. Städel Museum, Frankfurt am Main, St.F.3595. Online: <https://sammlung.staedelmuseum.de/de/werk/adam-opel-ag-ruesselsheim-1> (PD).

FIGURES

FIG. 1 Taxonomy of body-related behavior using the features *static*, *conventionalized*, *semanticized*, and *encoded*; adapted from Doris Schöps (2012). "Semantik und Pragmatik von Körperhaltungen im Spielfilm." In: *IMAGE. Zeitschrift für interdisziplinäre Bildwissenschaft* 8.2, 5–33, here 7. Online: <https://doi.org/10.25969/mediarep/16553>.

FIG. 2 Book structure with associated research objectives.

FIG. 3 Digital *Warburgean Board* of body-related models. Straight lines indicate more direct relationships; dotted lines represent looser ones. From top left to bottom right: Eckhard Leuschner (2020). *Maßfiguren. Körpernormen und Menschenbild in Kunst- und Architekturtheorie des 20. Jahrhunderts.* Vol. 172. Studien zur internationalen Architektur- und Kunstgeschichte. Petersberg: Michael Imhof, 19, 185, 146, 21; Carlo Blasis (1830). *The Code of Terpsichore: The Art of Dancing: Comprising Its Theory and Practice, and a History of Its Rise and Progress, from the Earliest Times.* Trans. by R. Barton. London: Edward Bull, 97; Pirkko Rathgeber (2019). *Bewegungsfiguren. Über die Bewegung der Strichfigur in der Zeichnung und ihre Bedeutung für den Zeichentrickfilm*. Paderborn: Wilhelm Fink, 604; Bernhard Klemm (1901). *Katechismus der*

Tanzkunst. Ein Leitfaden für Lehrer und Lernende. Leipzig: J.J. Weber, 216; Henry Dreyfuss (1960). *The Measure of Man: Human Factors in Design.* New York: Whitney, Cover; Georg Heinrich Werner (1796). *Gründliche Anweisung zur Zeichenkunst durch die Geometrie. Mit vielen Kupfern.* Göttingen: Joh. Christ. Dan. Schneider, Tab. VII. Online: <https://doi.org/10.11588/diglit.18823#0708>; Georg Lichtensteger (1746). *Die aus der Arithmetic und Geometrie heraus geholten Gründe zur Menschlichen Propportion.* Nuremberg: Fleischmann, Tab. I, II; Johann Daniel Preissler (1740). *Die durch Theorie erfundene Practic, oder Gründlich-verfasste Reguln, deren man sich als einer Anleitung zu berühmter Künstlere Zeichen-Wercken bestens bedienen kan.* Nuremberg, Taf. 3; Paul Richer (1893). *Canon des proportions du corps humain.* Paris: Ch. Delagrave, Pl. IV. Online: <https://gallica.bnf.fr/ark:/12148/bpt6k83040k>; Heimo Kuchling (2003). *Oskar Schlemmer. Der Mensch. Unterricht am Bauhaus. Nachgelassene Aufzeichnungen.* Ed. by Hans M. Wingler. Neue Bauhausbücher. Berlin: Gebr. Mann, 89, 91; Étienne-Jules Marey (1885). "Développement de la méthode graphique par l'emploi de la photographie." In: *La méthode graphique dans les sciences expérimentales et principalement en physiologie et en médecine*, 34. Online: <https://gallica.bnf.fr/ark:/12148/bpt6k6211377v>; Barry Rosen and Michaela Unterdörfer, ed. (2007). *Allan Kaprow: 18 Happenings in Six Parts.* Göttingen: Steidl, no page numbers; Heinrich Lautensack (1564). *Des Zirkels und Richtscheits auch der Perspektiva und Proportion der Menschen und Rosse kurze und gründliche Unterweisung des rechten Gebrauchs ... für Goldschmiede, Maler, Bildhauer, Steinmetze usw.* Frankfurt am Main, fol. 45r, 46v, 49v; Amaranthe Roulliet (1857). *Principles de dessin. Divisions de la tête et de la figure académique, suivies de quelques notions de perspective. Pour servir de complément au procédé du même auteur, acquis et publié par le Gouvernement en 1844.* Paris, Planche 8. Online: <https://doi.org/10.11588/diglit.18717#0033>; Gérard de Lairesse (1784). *Großes Mahler-Buch. Worinnen die Mahlerey nach allen ihren Theilen gründlich gelehret, durch vernünftige Raisonnements über Gemählde erklärt, und aus den besten Kunststücken der alten und neuen berühmtesten Mahler in Kupferstichen deutlich dargestellt wird.* Nuremberg, pag. 29. Online: <https://doi.org/10.11588/diglit.1231#0039>; Rathgeber (2019, 582–585); Wassily Kandinsky (1926). "Tanzkurven. Zu den Tänzen der Palucca." In: *Das Kunstblatt* 10.3, 117–121, here 119; Erhard Schön (1542). *Vnnderweisung der proportzin vnnd stellung der possen.* Nuremberg: Stadtbibliothek Nürnberg, fol. CIIa, CIIb, CIIc; Ernst Ullmann (1958). *Die Lehre von den Proportionen.* Dresden: Verlag der Kunst, Cover; Albrecht Dürer (1905). *Das Skizzenbuch von Albrecht Dürer in der Kö-*

nigl. Öffentl. Bibliothek zu Dresden. Strasbourg: Heitz, Taf. 62. Online: <http://digital.slub-dresden.de/id367587874>; Carl Heinrich Stratz (1904). *Naturgeschichte des Menschen. Grundriss der somatischen Anthropologie.* Stuttgart: Enke, 286; Rudolf Martin (1914). *Lehrbuch der Anthropologie in systematischer Darstellung. Mit besonderer Berücksichtigung der anthropologischen Methoden.* Jena: Gustav Fischer, 43, 45; Fritz Kahn (1927). *Das Leben des Menschen. Eine volkstümliche Anatomie, Biologie, Physiologie und Entwicklungsgeschichte des Menschen.* 5 vols. Stuttgart: Kosmos, 68. Some images cannot be displayed because their rights could not be clarified; these are marked with light brown rectangles.

FIG. 4 Successive postures of a runner's limbs. On the top, the limbs are reduced to dots and lines by chronophotography; on the bottom, they are represented as a human skeleton in schematic form (from Étienne-Jules Marey [1885]. "Développement de la méthode graphique par l'emploi de la photographie." In: *La méthode graphique dans les sciences expérimentales et principalement en physiologie et en médecine*, 34, 37. Online: <https://gallica.bnf.fr/ark:/12148/bpt6k6211377v>).

FIG. 5 Detail from Marcel Duchamp (1912). *Nude Descending a Staircase, No. 2*. Philadelphia Museum of Art, Philadelphia, 1950-134-59. Online: <https://en.wikipedia.org/wiki/File:Duchamp_-_Nude_Descending_a_Staircase.jpg> (Wikimedia Commons, PD).

FIG. 6 Detail from Jean Metzinger (1912–1913). *The Blue Bird*. Musée d'Art Moderne de la Ville de Paris, Paris. Online: <https://en.wikipedia.org/wiki/File:Jean_Metzinger,_1912-1913,_L%27Oiseau_bleu,_(The_Blue_Bird)_oil_on_canvas,_230_x_196_cm,_Mus%C3%A9e_d%27Art_Moderne_de_la_Ville_de_Paris..jpg> (Wikimedia Commons, PD).

FIG. 7 Point-based abstraction process; from Georg Heinrich Werner (1796). *Gründliche Anweisung zur Zeichenkunst durch die Geometrie. Mit vielen Kupfern*. Göttingen: Joh. Christ. Dan. Schneider, Tab. VII. Online: <https://doi.org/10.11588/diglit.18823#0708>.

FIG. 8 Point-based figures; from Gérard de Lairesse (1784). *Großes Mahler-Buch. Worinnen die Mahlerey nach allen ihren Theilen gründlich gelehret, durch vernünftige Raisonnements über Gemählde erklärt, und aus den besten Kunststücken der alten und neuen berühmtesten*

Mahler in Kupferstichen deutlich dargestellt wird. Nuremberg, 29. Online: <https://doi.org/10.11588/diglit.1231#0039>.

FIG. 9 Point-based figures; from Amaranthe Roulliet (1857). *Principles de dessin. Divisions de la tête et de la figure académique, suivies de quelques notions de perspective. Pour servir de complément au procédé du même auteur, acquis et publié par le Gouvernement en 1844*. Paris, Planche 8. Online: <https://doi.org/10.11588/diglit.18717#0033>.

FIG. 10 Line-based figures; from Heimo Kuchling (2003). *Oskar Schlemmer. Der Mensch. Unterricht am Bauhaus. Nachgelassene Aufzeichnungen*. Ed. by Hans M. Wingler. Neue Bauhausbücher. Berlin: Gebr. Mann, 89.

FIG. 11 Grouping rules of a *body plan*, denoted by arrows, control the assembly of basic groups, e.g., *body segments*, into advanced groups, e.g., *limb–segment girdles*; unimplemented rules are indicated by dashed lines (from Margaret M. Fleck et al. [1996]. "Finding Naked People." In: *Computer Vision – ECCV 1996 – 4th European Conference on Computer Vision*. Ed. by Bernard F. Buxton and Roberto Cipolla. Vol. 1065. Lecture Notes in Computer Science. Springer, 593–602, here 596. Online: <https://doi.org/10.1007/3-540-61123-1_173>).

FIG. 12 The costume's transformation of the human body; from Oskar Schlemmer (1925). "Mensch und Kunstfigur." In: *Die Bühne im Bauhaus*. Munich: Albert Langen, 7–43, here 16–17. Online: <https://doi.org/10.11588/diglit.29477#0013>.

FIG. 13 Distinction between bounding box and keypoint annotation: as shown in Andrea del Sarto's *Pietà with Saints* (1523–1524), human figures are first enclosed by bounding boxes; then up to 17 keypoints are assigned, indicated by green circles in the detail view (<https://commons.wikimedia.org/wiki/File:Andrea_del_Sarto_-_Piet%C3%A0_with_Saints_-_WGA0395.jpg> [Wikimedia Commons, PD]).

FIG. 14 Depiction styles of the PoPArt data set, ranging from impressionistic to neo-figurative and realistic variants. For each style, an example image is shown (all Wikimedia Commons, PD).

FIG. 15 Challenges to art-historical figure annotation include: (i) the size of figures, (ii) the spatial relationships between them, (iii) deviations from the 'ideal' human form, and (iv) the positioning of the human body.

FIG. 16 Sample images from the PoPArt data set, illustrating the challenges of labeling art-historical figures: (i) the size of figures, (ii) the spatial relationships between them, (iii) deviations from the 'ideal' human form, and (iv) the positioning of the human body (all Wikimedia Commons, PD).

FIG. 17 Example view of the web-based open-source COCO Annotator (<https://github.com/jsbroks/coco-annotator> [screen capture 4 March 2024]).

FIG. 18 Posture skeletons that deviate most from the mean posture skeleton for each depiction style within the PoPArt data set.

FIG. 19 PoPArt figure annotation, displayed next to its corresponding image annotation, following the JSON-based Microsoft COCO format (Tsung-Yi Lin et al. (2014). "Microsoft COCO: Common Objects in Context." In: *Computer Vision – ECCV 2014*. Ed. by David Fleet et al. Cham: Springer, 740–755. Online: <https://doi.org/10.1007/978-3-319-10602-1_48>).

FIG. 20 Detail from John Martin (1834). *The Deluge*. Yale Center for British Art, New Haven, B1978.43.11. Online: <https://commons.wikimedia.org/wiki/File:John_Martin_-_The_Deluge_-_Google_Art_Project.jpg> (Wikimedia Commons, PD).

FIG. 21 Detail from Nicolas Poussin (1660–1664). *Winter or The Deluge*. Musée du Louvre, Paris, INV 7306 and MR 2336. Online: <https://commons.wikimedia.org/wiki/File:Poussin_-_L%27Hiver,_1660-1664,_INV_7306_;_MR_2336.jpg> (Wikimedia Commons, PD).

FIG. 22 The top-down approach to HPE first detects human figures within a given scene, here in Andrea Mantegna's *Christ as the Suffering Redeemer* (c. 1488–1500); delineates them with bounding boxes; and then determines keypoints for each figure (<https://commons.wikimedia.org/wiki/File:Kristus_som_den_lidende_frelser.jpg> [Wikimedia Commons, PD]).

FIG. 23 The bottom-up approach to HPE first detects keypoints in Mantegna's *Christ as the Suffering Redeemer* (c. 1488–1500) and then merges them to identify figures and their bounding boxes (<https://commons.wikimedia.org/wiki/File:Kristus_som_den_lidende_frelser.jpg> [Wikimedia Commons, PD]).

FIG. 24 In the first stage of HPE, the image is processed by a CNN backend. Using positional encoding, it is used as input to a transformer model that predicts a fixed set of bounding boxes. After filtering out irrelevant detections, the boxes are cropped from the original image. These cropped boxes, each containing a human figure, are fed into the second stage of the estimation process that uses another transformer to compute a set of keypoints for each cropped box (<https://commons.wikimedia.org/wiki/File:Kristus_som_den_lidende_frelser.jpg> [Wikimedia Commons, PD]).

FIG. 25 The semi-supervised training pipeline is designed to handle both labeled and unlabeled images. The teacher model initially employs weakly augmented data to generate bounding boxes and keypoints, 'pseudo-labels,' which are subjected to a thresholding process based on the teacher model's predictions. After this process, the refined pseudo-labels are aligned with the coordinate system of the strongly augmented images (<https://commons.wikimedia.org/wiki/File:Master_Of_The_Vienna_Adoration_-_Adoration_-_WGA14636.jpg> [Wikimedia Commons, PD]).

FIG. 26 Positive and negative predictions on the labeled PoPArt data set (*orange*) versus predictions on the unlabeled ART500K data set (*blue*). For bounding box detection, the teacher model underestimates the number of bounding boxes compared to the actual occurrences in the data (*top*); for keypoint detection, the teacher model predicts a larger number of keypoints than actually present in the data (*bottom*).

FIG. 27 Model predictions overlaid with examples from PoPArt. 'ST' indicates the inclusion of style-transferred material in the model (all Wikimedia Commons, PD).

FIG. 28 Based on the estimated whole-body posture, shown in *blue*, the upper-body (*green*) and lower-body (*red*) are segregated in the three-stage approach to HPR. The whole body, upper body, and lower body constitute the query: in a pre-processing step, they are filtered with a threshold and then compressed into a 320-dimensional view-invariant pose embedding. To classify each body configuration, the cosine distance between the respective embedding and the embeddings of the support set is employed. For visualization purposes, the 320-dimensional pose embeddings are reduced to a two-dimensional format.

FIG. 29 Close-ups of sample images for each direct subnotation of the relevant groups of Iconclass notations. Inapplicable notations are not visualized (all Wikimedia Commons, PD).

FIG. 30 Distribution of creation dates in art-historical Wikidata object entities. Using only the earliest date of creation causes many data points to converge around the turn of the centuries, leading to an inaccurate peak in the number of objects (*top*). Bootstrapping not only simulates the likely distribution of creation dates but also produces a more balanced distribution that accounts for uncertainty (*bottom*).

FIG. 31 Confidence scores and scale categories for the PoPArt test data set. Using the available ground-truth annotations, detections are classified as either positive (*green*) or negative (*red*) for bounding boxes (*top*) and keypoints (*bottom*), respectively.

FIG. 32 Binary XGBoost decision tree (Tianqi Chen and Carlos Guestrin [2016]. "XG-Boost: A Scalable Tree Boosting System." In: *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. Ed. by Balaji Krishnapuram et al. New York: ACM, 785–794. Online: <https://doi.org/10.1145/2939672.2939785>). cs_{bbox} is the confidence score of the bounding box; cs_{kp} the mean confidence score of the keypoints. The leaf estimates are log-odds.

FIG. 33 Confidence scores and scale categories for the Wikidata data set. Using a binary XGBoost decision tree (Tianqi Chen and Carlos Guestrin [2016]. "XG-Boost: A Scalable Tree Boosting System." In: *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. Ed. by Balaji Krishnapuram et al. New York: ACM, 785–794. Online: <https://doi.org/10.1145/2939672.2939785>), detections are classified as either positive (*green*) or negative (*red*) for bounding boxes (*top*) and keypoints (*bottom*), respectively.

FIG. 34 Queries for the retrieval study with art-historically relevant posture configurations (all Wikimedia Commons, PD).

FIG. 35 Annotated page from the retrieval study: 'relevant' images have a green tick, and 'irrelevant' ones have a red cross (screen capture 4 March 2024).

FIG. 36 Scatter plots, two-dimensional histograms, and contour plots of the reduced two-dimensional whole-body, upper-body, and lower-body embedding spaces, respectively.

FIG. 37 Scatter plot of the two-dimensional whole-body embedding space. Three groups can be identified: two that are attributed to specific configurations of the arms or legs, respectively; and another with rather unspecific features. Erroneous pose estimates are marked in *red*.

FIG. 38 Contour plots of the two-dimensional whole-body embedding space by Iconclass notation. For each notation, the postures of 500 human figures that are most similar to the respective reference posture in the support set were filtered.

FIG. 39 Contour plots of the two-dimensional upper-body embedding space by Iconclass notation. For each notation, the postures of 500 human figures that are most similar to the respective reference posture in the support set were filtered.

FIG. 40 Contour plots of the two-dimensional lower-body embedding space by Iconclass notation. For each notation, the postures of 500 human figures that are most similar to the respective reference posture in the support set were filtered.

FIG. 41 Bootstrapped distribution of creation dates in Wikidata object entities labeled with "crucifix."

FIG. 42 Scatter plots, two-dimensional histograms, and contour plots of the reduced two-dimensional whole-body, upper-body, and lower-body embedding spaces of images labeled with "crucifix," respectively.

FIG. 43 Distribution of whole-body posture similarities in images labeled with "crucifix" (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 44 Distribution of whole-body posture similarities in images labeled with "crucifix" and within the 10^{th} contour line (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 45 Distribution of upper-body posture similarities in images labeled with "crucifix" (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*)

by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 46 Distribution of upper-body posture similarities in images labeled with "crucifix" and within the 10th contour line (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 47 Distribution of lower-body posture similarities in images labeled with "crucifix" (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 48 Distribution of lower-body posture similarities in images labeled with "crucifix" and within the 10th contour line (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 49 Whole-body HPR results for the thief to Christ's right in James Tissot's *The Strike of the Lance* (1886–1894; a) with the estimated keypoints in *green* (all Wikimedia Commons, PD).

FIG. 50 Bootstrapped distribution of creation dates in Wikidata object entities labeled with "fall of man."

FIG. 51 Scatter plots, two-dimensional histograms, and contour plots of the reduced two-dimensional whole-body, upper-body, and lower-body embedding spaces of images labeled with "fall of man," respectively.

FIG. 52 Distribution of whole-body posture similarities in images labeled with "fall of man" (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 53 Distribution of whole-body posture similarities in images labeled with "fall of man" and within the 10th contour line (*green*) compared to the distribution of posture similarities in the remaining images within

the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 54 Distribution of upper-body posture similarities in images labeled with "fall of man" (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 55 Distribution of upper-body posture similarities in images labeled with "fall of man" and within the 10th contour line (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 56 Distribution of lower-body posture similarities in images labeled with "fall of man" (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 57 Distribution of lower-body posture similarities in images labeled with "fall of man" and within the 10th contour line (*green*) compared to the distribution of posture similarities in the remaining images within the Wikidata data set (*red*) by Iconclass notation. Only the 10 notations with the highest mean absolute difference in posture similarity between the groups are displayed.

FIG. 58 Whole-body HPR results for Eve in a copy after Albrecht Dürer's *Fall of Man* (1600–1625; a) with the estimated keypoints in *green* (all Wikimedia Commons, PD).

FIG. 59 Subset of detected human figures in Wikidata object entities labeled with "crucifix" (all Wikimedia Commons, PD).

FIG. 60 Upper-body HPR results for Christ in Marcello Venusti's *Christ on the Cross* (1500–1625; a) with the estimated keypoints in *green* (all Wikimedia Commons, PD).

FIG. 61 Upper-body HPR results for Christ in Diego Velazquez's *Christ Crucified* (1632; a) with the estimated keypoints in *green* (all Wikimedia Commons, PD).

FIG. 62 Upper-body HPR results for Christ in Peter Paul Rubens' *Expiring on the Cross* (1619; a) with the estimated keypoints in *green* (all Wikimedia Commons, PD).

FIG. 63 Subset of detected human figures in Wikidata object entities labeled with "fall of man" (all Wikimedia Commons, PD).