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RESEARCH ARTICLE

Whole-Drawer Imaging of Entomological Collections: Benefits, Limitations and Alternative Applications

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This paper examines current progress in whole-drawer imaging (digitization) of insect collections, and the advantages and disadvantages of different methods used. Based on their own experiences in whole-drawer imaging and the subsequent curatorship of virtual collections the authors discuss: 1) possible modifications of the technique suitable for small collections and museums, 2) optical limitations of the technique, 3) advantages and disadvantages of curating virtual collections, and 4) other possible applications of whole-drawer imaging.

Keywords: digitizing; virtual collections; insects; telecentric optics; stitching artefacts; alternative techniques; remote curation

1. Introduction

Gathered since the Middle Ages, natural history collections represent a historically and scientifically important sample of the world's biological heritage, and form the basis of hundreds of years of fundamental and applied research. Their usefulness for modern science depends not only on their historical significance, taxonomic importance, and geographic scope, but also on their availability to researchers worldwide. Recent advances in digital technology and communications have made it possible to share vast amounts of information worldwide almost instantly, leading to the development of various methods of digitization of natural history collections not only for the biological insect specimens discussed here, but also for other kinds of biological and geological specimens.

Insects are an invaluable, often predominant part of natural history collections, making digitization of insect specimens one of the most actively discussed topics in the curation of zoological and entomological collections. It is often estimated that it will take hundreds or even thousands of years for large museums to digitize each individual insect specimen using current methods (Bergsten and Holovachov 2014). Museums need faster techniques, for which the solution appears to be 'whole-drawer imaging'. This is a method whereby an entire drawer containing multiple (sometimes hundreds) insect specimens is digitized in a single high-resolution image, which is displayed online. Several nearly identical whole-drawer imaging technologies have been developed in recent years. Their main advantage is that they offer a much faster rate of digitization of insect collections compared with conventional methods. But what are the limitations of these technologies? How can they be improved? Are there alternatives? We will explore these technical issues, as well as investigate effects on the work of curators and some implications for conservation of the specimens. We will then draw broader conclusions, such as the possible benefits for the wider scientific community and what it offers for the general public? We address these issues by drawing from our experience using whole-drawer imaging to digitize the historically important insect collection of Ernst Friedrich Germar (1786–1853) at the Zoological Museum of the Ivan Franko National University of Lviv.

2. Review of Existing Technologies

Modern technology has created the grounds for the development and implementation of novel approaches towards the mass digitization of natural history collections; it is not surprising that several groups of researchers independently developed very similar methods for digitizing whole insect drawers almost simultaneously. All of these methods create ultra-high resolution images of the entire insect drawer, much larger in size than a single picture taken with a conventional digital camera (**Figure 1**). The size of such images ranges from a few hundred megapixels to a few gigapixels, compared to a maximum of 36 megapixels in currently available digital single-lens reflex (SLR) and mirrorless cameras, or 80 megapixels in digital medium format cameras. The resulting ultra-high resolution images of entire insect drawers are published online using algorithms that manage a pyramid of tiles, created at different magnifications and at different resolutions. This means that the software creates several versions of

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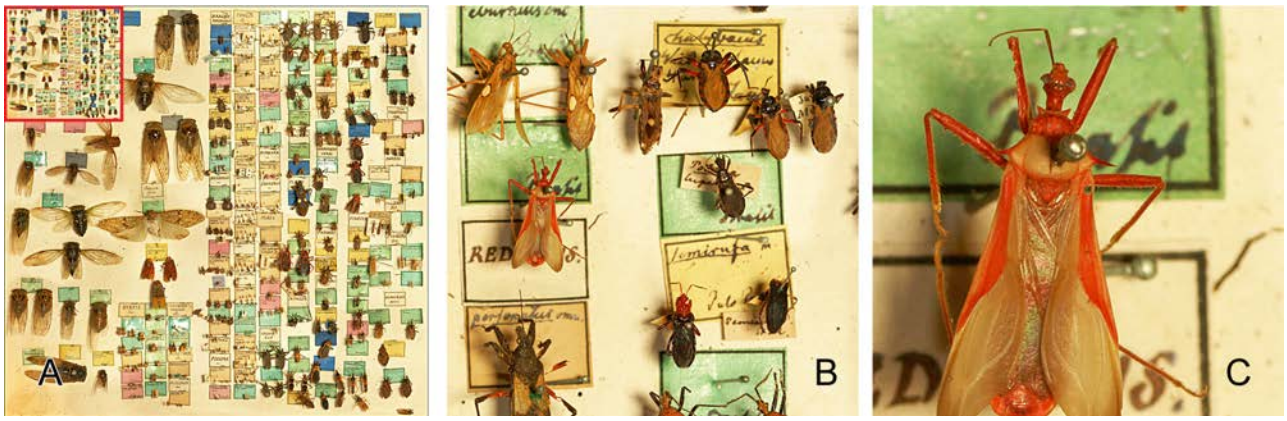

Figure 1: Increase in resolution between single-shot and multi-shot composite image of the insect drawer: **A**, size comparison between 16 megapixel (average resolution of currently available consumer-grade digital cameras) and 210 megapixel images; **B**, 100% crop from the 16 megapixel image; **C**, 100% crop from the same area of 210 megapixel image.

the original (ultra-high resolution) image at different scales. It downsizes the original image to, for example 50 per cent, 25 per cent, 12.5 per cent and so on, of its size and saves these copies. Each copy is then split into many small individual files called 'tiles', which are saved in subfolders. As a result, the original image is converted into a series of subfolders within one root folder, each including a set of tiles created from one of the downsized copies of the ultra-high resolution image. This root folder is hosted on a server and displayed online with the aid of additional software. It displays these tiles seamlessly and allows users to view images of entire insect drawers, pan through them, and zoom in on individual specimens. This enables researchers to examine morphological details at the highest possible magnification and often to read the label, which is of particular importance. The main whole-drawer imaging systems are as follows:

2.1 GigaPan™

The team at North Carolina State University (NCSU) has utilized the GigaPan robot (see GigaPan website), originally designed for landscape and architectural photography, in combination with a fixed-lens digital camera to produce whole-drawer images of the NCSU Insect Museum (Bertone *et al.* 2012). The GigaPan robot is controlled via proprietary software and the final images are produced with GigaPan Stitcher. The resulting whole-drawer images show noticeable curvature towards the edges of the frame, caused by the fact that the camera is fixed above the middle of the drawer; objects furthest from the centre of the drawer are imaged not vertically, but at an angle, and the stitching software has to use non-orthographic projection to create the final panorama. Since insects around the edges of the image are displayed at an angle and somewhat distorted (**Figure 2a**), it is impossible to correctly assess their size and proportion for identification purposes or morphometric studies.

2.2. SatScan®

The research team at the Natural History Museum in London, in collaboration with SmartDrive® Limited, have developed SatScan (Blagoderov *et al.* 2012). This imaging system consists of an industrial camera with an object-space telecentric lens attached to a rail system, which can move the camera horizontally and vertically (for focus stacking). Mechanical operations and the stitching of images are controlled by custom proprietary software. The use of the object-space telecentric lens avoids perspective errors (see also Section 4.1, below) and the rail system that pans the camera along the XY coordinate system allows the creation of error-free and distortion-free gigapixel panoramic images. Such a system has a narrower field of view and lower resolution of the input images, compared to high-resolution prosumer photographic lenses and more than 12 megapixel digital cameras used in other setups. It therefore requires the processing of a greater number of input images to achieve the same image size and resolution. Images created with the SatScan system provide a sufficient amount of morphological information for the remote identification of species (Mantle *et al.* 2012) and the system is now being used not only in the Natural History Museum, but also in the Naturalis Biodiversity Centre (Leiden), the Museum für Naturkunde (Berlin) (Schurian personal communication) and the Australian National Insect Collection (Canberra) (Fisher 2013). A relatively similar system utilizing telecentric optics and a machine vision camera has also been recently discussed by D Raila (2013).

2.3 DScan

This system was developed in the Zoologische Staatssammlung in Munich, Germany, and consists of a consumer digital SLR camera with a photographic macro lens attached to the linear units used by computer numerical control positioning machines and controlled with proprietary software (Schmidt *et al.* 2012). For image stitching, the DScan system uses commercially available AutoPano Giga software. Similar to SatScan, the DScan produces panoramic images with minimal distortion, but the use of a regular photographic lens that is not object-space telecentric can create perspective errors, which may result in stitching artefacts for large-sized insect specimens (see Section 4.1).

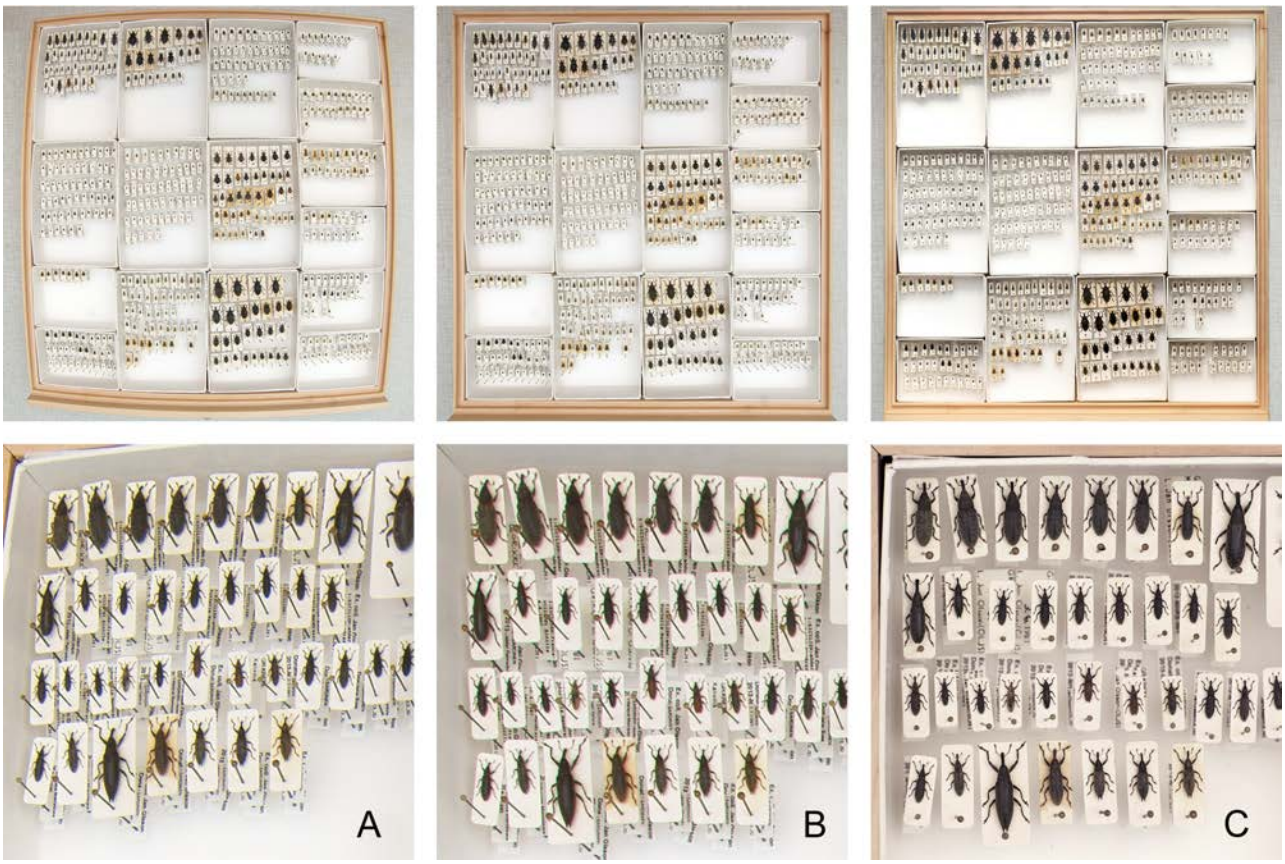

Figure 2: Different type of distortion produced by different digitizing techniques showing entire drawer (upper row) and crop from the top-left corner from the drawer (bottom row): **A**, barrel-shaped distortion; **B**, perspective distortion; **C**, minimal distortion/parallel projection.

2.4 Micro GigaPan

The original Micro GigaPan system also consists of a consumer digital SLR camera with a photographic macro lens attached to the Probotix™ Fireball three-axis rail system, and operated with the aid of custom software (Longson *et al.* 2010); stitching of images is completed with commercially available programs (Zerene Stacker, AutoPano Giga or GigaPan Stitcher). The original advantage of the Micro GigaPan system over other similar systems was the initial implementation of extended focus techniques (focus stacking). Subsequent iterations of the system include the 'Gigapixel Micro Imager' prototype and the GIGAmacro™ Magnify[2] professional photography system (see Micro GigaPan and GIGAmacro websites), which include the important improvement involving a telecentric auxiliary lens attached to the photographic macro lens, making the imaging system nearly telecentric, and improving the workflow.

2.5 High-Resolution Medium Format Camera

Hasselblad offers a medium format camera system with a 50 megapixel digital back, which is equipped with a specially developed piezo-frame module (see Hasselblad website). In the 'Six-shot, 200Mpix Multi-shot' mode the sensor of the camera moves along the XY axis at sub-pixel distances, capturing six 50 megapixel images of the same field of view. These six images are then merged to create a single high-resolution 200 megapixel photograph. As a result, resolution of the final picture is increased not by merging input images with partially overlapping fields of view, but by employing super-resolution algorithms. Therefore, this system does not have to deal with stitching artefacts, but the image will still exhibit perspective errors and distortion towards the edges (**Figure 2b**). The original H4D-200MS Hasselblad camera was used to photograph insect collections in the Queensland Museum in Australia (Thompson 2013), and can be optionally mounted on the focusing rail (Z axis) for focus stacking.

Table 1 provides a quick comparison of the different systems, including approximate costs (where known).

3. The Digitization of Germar's Collection of *Hemiptera* and *Homoptera*

All of the technological solutions presented above are methodologically sound and effective; they are well-suited for the mass digitization of insect collections by the organizations that can afford them. These new methods and technologies are typically developed by collaboration between industry and leading museums, focusing on speed, effectiveness and automatism. However, the affordability of these technologies to the end user is rarely taken into consideration. For example, all of the setups mentioned above require a full-time technician to operate, but this point is frequently omitted when discussing costs; these costs will vary greatly according to country, and in some cases volunteers may be used.

Unfortunately, in many countries (and indeed within smaller museums of wealthier nations), financial support

Name and authors	Optical component	Recording component	Mechanical component	Software component	Cost per unit (US$)
GigaPan (Bertone *et al.* 2012)	Fixed lens (non-telecentric)	digital camera	GigaPan robot	Commercial	1,500
SatScan (Blagoderov *et al.* 2012)	Machine vision telecentric lens	Machine vision camera	XYZ linear robot	Proprietary	Unknown
DScan (Schmidt *et al.* 2012)	Non-telecentric lens	SLR camera	XY linear robot	Proprietary and Commercial	25,000
Micro GigaPan (Longson *et al.* 2010)	Non-telecentric lens	SLR camera	XYZ linear robot	Proprietary and Commercial	Unknown
Gigapixel Micro Imager (see Micro GigaPan website)	Non-telecentric lens with telecentric attachment	SLR camera	XYZ linear robot	Proprietary and Commercial	Unknown
GIGAmacro Professional Photography System (see GIGAmacro website)	Non-telecentric lens with telecentric attachment	SLR camera	XYZ linear robot	Proprietary and Commercial	48,000
Hasselblad H4D-200MS or H5D-200MS (Thompson 2013)	Non-telecentric lens	Medium format camera	Fixed stage, Z rail	Proprietary	50,000

Table 1: Comparison of Currently Available Whole-Drawer Imaging Systems.

for museums will not cover the cost of such imaging systems. For example, there are more than 25 natural history museums housing entomological collections in the Ukraine alone (Shydlovskyy 2012). Together, they hold over five million preservation units (each of which can be one insect specimen or an entire drawer with hundreds of insects), collected not only from the territory of Ukraine and the former Soviet Union, but also from other countries around the world. Some of these smaller museums may not hold a high percentage of type material or undiscovered new species within their collections, but the chronological and geographical data for the known species that they house is extremely valuable for biogeographic studies. For example, such data is important for the study of historical changes in the distribution of species, including presently endangered and extinct taxa, or indeed, invasive organisms (Pyke and Ehrlich 2010). None of the Ukrainian natural history museums can afford any of the whole-drawer digitizing systems described above. Therefore, it was necessary for us to create a more affordable version of the whole-drawer technique for the digitization of the important Germar Collection at the Zoological Museum of the Ivan Franko National University of Lviv, as discussed below.

3.1 Historical Background

Ernst Friedrich Germar (1786–1853) is best known for his research in geology, although his scientific interests were equally divided between entomology, palaeontology and geology (Hauschke 2001; Shydlovskyy 2009). His entomological collection was founded at the beginning of the nineteenth century when he purchased the collection of Herr Hübner (Shaum 1853). The collection grew over time, enriched by insect specimens from all over the world. This provided the basis for Germar's research on the diversity of *Heteroptera*, *Homoptera* and *Coleoptera*, and includes most, if not all, of his type material. At the turn of the century, part of Germar's entomological collection was purchased by Count Mniszek for the growing Zoological Museum of Lviv University, where it has remained since.

Although it has been indicated that this collection was lost during the Second World War, in fact it remained safely stored at the museum, together with other nineteenth century collections (O'Brien 1991; Schröder 1957). The museum archives document numerous enquiries about this collection from scientists all over the world, demonstrating that its existence was known to some researchers, but remained lost to the wider scientific community due to the political situation in the country (Carvalho and Webb 2005; Horn *et al.* 1990). To the best of our knowledge, throughout the twentieth century, the collection was only briefly studied by Dr IM Kerzhner from the Zoological Institute in St Petersburg, Russia, and by Dr A Jansson from Finland (Jansson 1986). Information about the availability of the collection for researchers started to become more widespread at the beginning of the twenty-first century, and since then, numerous type specimens have been studied by researchers worldwide (Duffels 2011; Mejdalani *et al.* 2006; Simões and Campos 2014; Takiya *et al.* 2006).

3.2 The Collection: Composition and Importance

Germar's collection consists of two parts: the collection of *Homoptera* and the collection of *Hemiptera*. It includes a total of 4,500 specimens of over 1,800 species collected from all over the world (with the exception of Antarctica), and described by Germar in his publications. A significant proportion of the species' names bear the mark '*m*', that is, '*mihi*', translated from Latin as 'mine', indicating the species that Germar considered to be new to science. Only some of these names were actually published by Germar himself (for example, Germar 1821); several were subsequently published by other researchers (Herrich-Schäffer 1844; Taschenberg 1884). The total number of type specimens in this collection is yet to be determined. The remaining part of the collection also has

great historical significance, especially as the specimens are over 170-years-old and still relatively well-preserved (**Figure 3A-F**).

The entire collection is organized in ten large wooden boxes and all specimens are arranged systematically (**Figure 3G**). The label bearing the species names, synonymous names (when applicable) and geographic localities is attached directly to the (inner) bottom of the box, and pinned insect specimens are arranged below the bottom side of the label. If there are several insects belonging to the same species, these are arranged in a horizontal or vertical row (depending on their size) below the actual label. The labels include written geographic information about where the specimens were collected (usually the name of the country, geographic area, island, closest large city and so on) and are also colour-coded based on their continent: green labels represent the Americas, white and pink for Europe, yellow for Asia, blue for Africa and purple represents Australia and Oceania (**Figure 3G**). In addition, many specimens have small individual labels, sometimes with handwritten or typed information on the locality or species name, and sometimes just numbers or letters of unknown significance. Labels with the genus name are positioned in front of the vertical rows of species assigned to each particular genus. As a result, all insect specimens are linked to the separately placed labels by their position in the box (unlike modern entomological collections, where the complete label is attached to the same pin as the insect specimen), and cannot be relocated or removed from the box without the need to create and attach new labels to them. Therefore, the entire collection needs to be preserved and studied 'as is' in its entirety.

Despite its historical and taxonomic importance, and great interest from many entomologists worldwide, Germar's collection remains relatively unstudied. The main obstacle is that specimens from this collection cannot be sent out, they can only be investigated by those willing and with the financial means to visit the Zoological Museum. The reasons for this restriction are political; laws and customs regulations in Ukraine are not satisfactory to guarantee unobstructed transportation of biological materials across the border. Therefore, it was imperative to create a way for researchers to study Germar's collection remotely; to check the state of preservation of the specimens, verify the correctness of the identification, search for possible type specimens or confirm their absence and so on. Since whole-drawer imaging of insect collections allows online display of high-quality, high-resolution pictures, extraction of morphological and geographic information and remote study access, it was the best way to make Germar's collection publicly accessible. However, there was a challenge – an extremely limited budget!

3.3 Digitization Process

In 2009, independently from the other teams discussed in Section 2 (above), we started to develop a low-cost imaging system for digitizing insect drawers. Inspired by recently published 'zoomable' images from the Göttingen herbarium, we wanted to make Germar's collection similarly available to the public (Schmull *et al.* 2005). Limited by the essentially non-existent budget, our tools were restricted to what was already present in the museum or personally owned by the authors. Our setup included a Sony digital SLR camera (either a Sony A100 or A700), fitted either with a Tamron 90mm F/2.8 macro lens or Minolta 100mm F/2.8 macro lens, and attached to a modified copy stand. The lighting was provided by flash units with diffusers. Focus, aperture, exposure, flash intensity and white balance were all set manually and consistently between photographic sessions. The stand with attached cameras was immobile. Instead, the insect drawers were moved manually along a pre-determined grid pattern. Although moving the drawer manually is less precise than the robotic movements utilized by the other setups discussed above, it has no impact on the quality of the resulting ultra-high resolution images, provided that the overlap between adjacent input pictures is large enough. The final ultra-high resolution images were created using freely available Hugin panorama stitching software (see Hugin website) from 80–130 original photographs. The use of non-telecentric optics resulted in some stitching artefacts (see section 4.1 for further details), which were corrected manually. The size of the final images after editing and cropping is 14.2–18.0 × 14.4–17.5 megapixels or about 200–315 megapixels of the surface area. These ultra-high resolution images were then displayed on the Zoological Museum's website with the aid of the free Zoomify™ plug-in.

3.4 Results

The content and the very existence of Germar's collection of *Hemiptera* and *Homoptera* were unknown to most scientists for a very long time. The first public overview of the smaller part of the collection was provided in the publication: '*Homopteran insects from the collection of E F Germar in the Zoological museum of LNU (Catalogue)*' (Shydlovskyy and Holovachov 2005). Scientific interest towards the collection then increased considerably and several research papers were published shortly afterwards (Duffels 2011; Mejdalani *et al.* 2006; Takiya *et al.* 2006). However, the current curatorial staff at the museum does not include trained entomologists, and so many questions posted by interested researchers could not be properly answered. The digital virtual collection has helped immensely. Not only can scientists from all over the world see the entire collection themselves, but they can also examine all specimens in detail (**Figure 3**), assess their preservation quality and suitability for further research, verify the identification and read most of the label data (Holovachov 2011). Although the digital collection was only made public in 2011, in the past three years we have already established a collaboration with several entomologists interested in a detailed re-evaluation of Germar's material, and the virtual collection itself has been cited in scientific papers (Mejdalani and Carvalho 2012). For now, zoomable images of Germar's *Hemiptera* and *Homoptera* are hosted on the server of the Ivan Franko National University of Lviv, which does not allow for the addition of metadata or other digital content. In the near future the images will also be mirrored in the international database

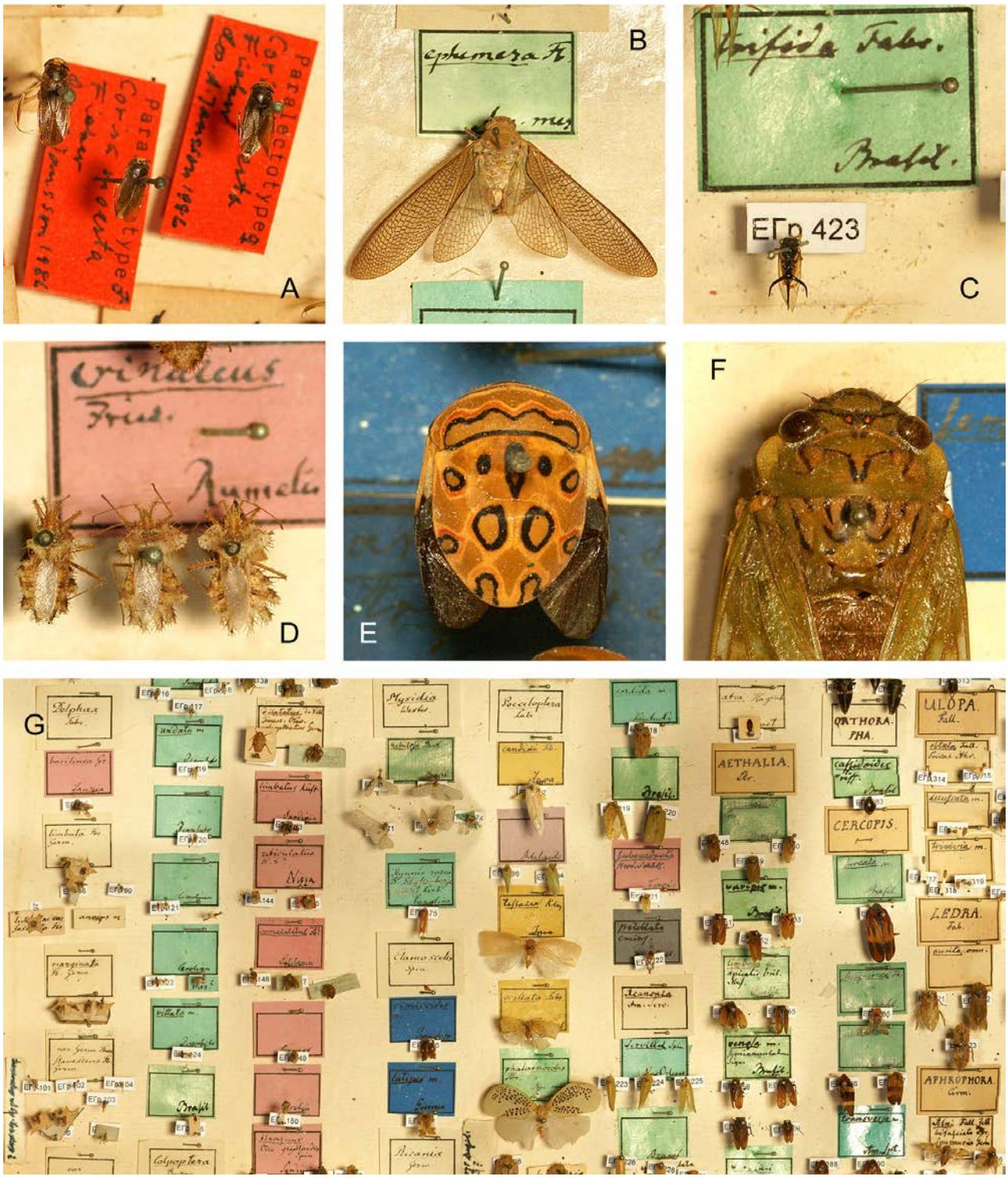

Figure 3: Examples from Germar's collection (original names preserved): **A**, *Corisa moesta*; **B**, *Pterodictya ephemera*; **C**, *Heteronota trifida*; **D**, *Phyllomorphus erinaceus*; **E**, *Pachycoris ocellus*; **F**, *Cicada semirlana*, **G**, large section of the box with different genera of *Homoptera*. Not to scale.

(under development) dedicated to the storage and sharing of whole-drawer ultra-high resolution images.

Our setup is the cheapest of those discussed in this paper, however this comes at the cost of slower performance (several drawers per day). It is only cost-effective when used for digitizing smaller collections, but it is also the only possible choice for museums with limited or no budget, of which there are very many, particularly in developing countries all around the world. Most such museums already have in their possession consumer-grade photographic equipment, which provides high-quality images and is suitable for use within digitization systems.

4. Limitations

4.1 Optical Limitations

The major drawback of our method, besides that it is slower and more labour intensive than the alternatives, is caused by the use of conventional, non-telecentric photographic

lenses. Contrary to ordinary photographic lenses, object-space telecentric lenses provide the same object magnification at all possible focusing distances. An object that is too close or too far from the focus plane and not in focus, will be the same size as if it were in focus. There is no perspective error and the image projection is parallel (see Edmund Optics website). Therefore, when such a lens is used to take images of pinned insects in a box, all vertical pins will appear strictly vertical, independent of their position within the camera's field of view (**Figures 4G** and **4H**). Perspective errors present in images taken with non-telecentric lenses will cause artefacts during the stitching process. Usually software algorithms will perform stitching along areas of low contrast and with few details, such as the bottom surface of the drawer, producing artefact-free results. However, problems occur most commonly with large insects or with insects with long appendages, which span across three or more original frames (**Figure 5**). Such artefacts must be manually corrected afterwards.

Currently available object-space telecentric lenses are designed for industrial applications (machine vision), but can also be used with conventional digital cameras with the appropriate adapters. Most such lenses are designed for smaller sensor cameras and will not cover the Advanced Photo System type-C (APS-C, so-called '1.5 crop') or 135 (so-called 'full-frame') sensor size of the consumer digital cameras with interchangeable lenses. Nonetheless, there are several telecentric lenses available that will cover a 28.7mm diameter image circle and are suitable for APS-C consumer digital SLR and mirrorless cameras, but are unsuitable for the full-frame cameras.

Such lenses should not be confused with currently produced photographic lenses, which are nearly telecentric on the image side. The chief rays from these lenses hit the digital sensors at an angle of incidence close to zero (nearly vertical), thus avoiding the corner shadowing that the digital sensors are sensitive to (the light hitting photo sites at an angle may not fully reach the bottom of the photo site, causing colour artefacts). These lenses are specifically designed for digital sensors, which perform best when light hits the sensor at an angle as close to a right angle as possible. However, objects photographed with such lenses will still exhibit perspective errors and distortion towards the edges.

4.2 Colour Management

Colouration of plants and animals is a very important diagnostic feature for species identification. The very first digitization attempts of herbarium specimens recommended including a colour standard during scanning, which has now become a mandatory part of the process (Schmull *et al.* 2005). It should be pointed out, however, that the mere inclusion of a colour standard in the picture is not sufficient to properly preserve and share the colour information of digitized specimens. When using digital cameras, two additional steps are necessary to consider. First of all, the colour temperature of light sources can change with time, depending on the type of lighting equipment used, and will cause minor colour variations in the resulting images. Therefore, using TIFF or JPG files straight from the camera may not be sufficient to preserve adequate colour information when minor differences are essential for identification purposes. In such cases, the white balance needs to be set individually for each image during conversion of the images from raw files to TIFF or JPG format.

Secondly, even if the images are properly calibrated and preserved in a standard colour space, they should still be examined by their prospective users with the aid of properly colour-calibrated monitors. Consumer-grade computer screens and monitors are set to the factory default colour space, which usually needs to be corrected to truthfully display fine colour gradations. The colours of every monitor, even those that have been previously corrected, change with time and age, and require periodical calibration. Printing full-colour images presents another problem. As discussed in detail by R Morris (Morris 2005), consumer-grade printers are not able to print the same colour gamut that digital cameras and monitors can record and display. As a result, printed illustrations often do not show subtle colour differences, which can be obvious on the computer monitor. Again, this may not be very important in the majority of cases, but when fine colouration differences are essential for the identification of digitized specimens, proper calibration of the screen used to view them, and proper profiling of the printer used to print images of these specimens needs to be taken into account.

4.3 Two-Dimensionality

The biggest drawback of whole-drawer imaging is their two-dimensionality (practical limitations 2 and 3, as discussed in Balke *et al.* 2013). Two-dimensional images are limited when it comes to showing the diagnostic characteristics of three-dimensional insects, notably when such features are located on the sides or underside of the insect and are thus invisible in the image. Similarly, labels located underneath the specimens are also often invisible in two-dimensional images. One of the peculiarities of the Germar Collection is the placement of labels separately from the insects. Most of the labels are not obscured by insect specimens, and, although not in perfect focus, they are still readable. This avoids the need to add label information separately in the form of metadata. Nevertheless, whilst not a major issue for the Germar Collection, the visibility of labels is a particularly significant factor to consider when creating whole-drawer images as it is very important for researchers to have access to label information.

At present, a whole-drawer image can be used as a 'map', where each specimen is linked to a separate file or set of files, showing the specimen from different sides, either as a series of photographs or as a three-dimensional image. Being able to examine specimens from all sides will also allow the viewer to see the text on the labels, which are located directly under the specimens. It is well understood, however, that the whole-drawer digitizing of insect collections needs to be transformed from two-dimensions to three-dimensions by employing complex imaging techniques (simultaneous use of multiple cameras positioned at different angles) and a digital workflow.

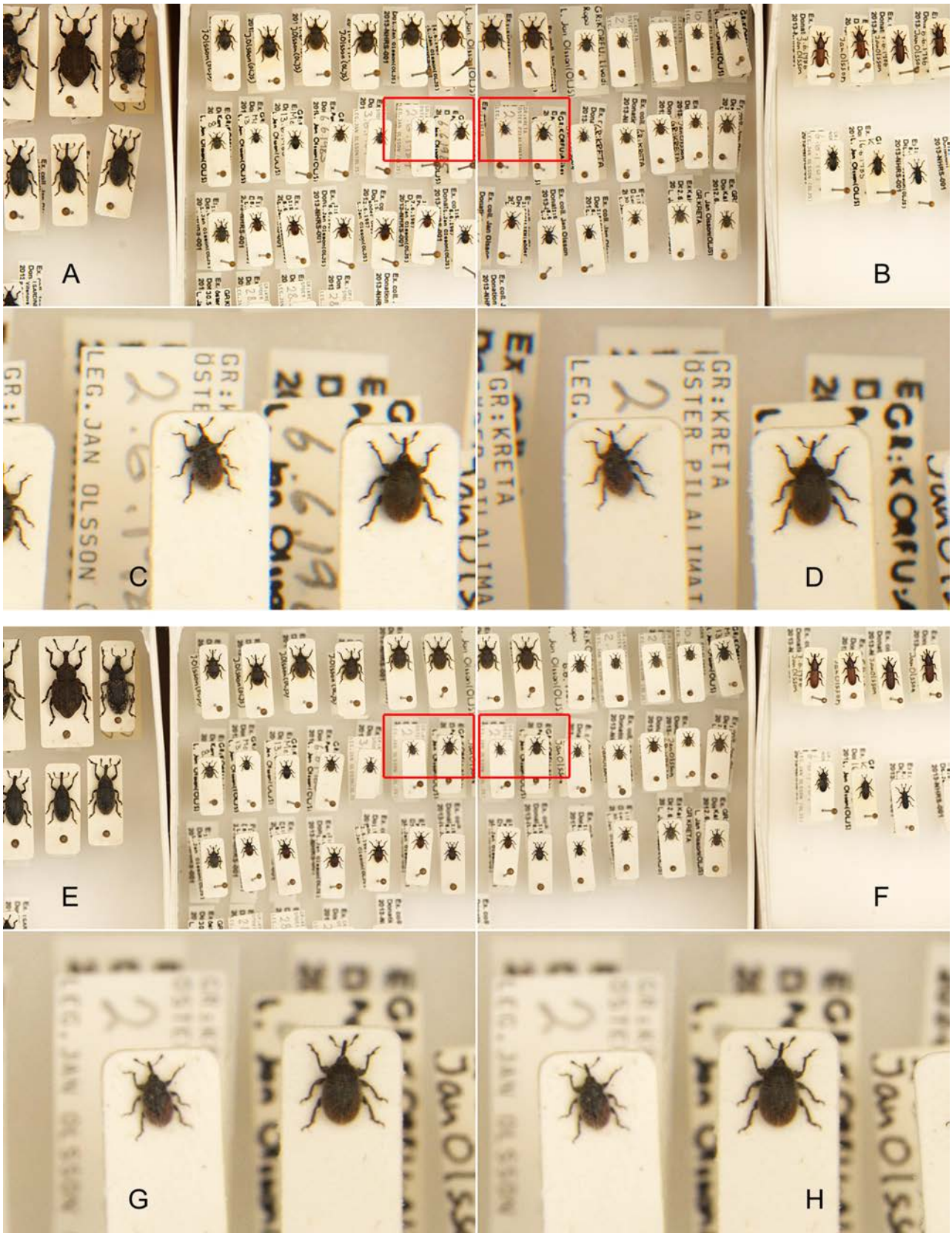

Figure 4: Differences in image rendering between conventional (**A-D**) and telecentric (**E-H**) lenses: **A** and **B**, a pair of overlapping input pictures taken with conventional lens; **C** and **D**, a pair of overlapping input pictures taken with telecentric lens; **E** and **F,** crops from overlapping portions of input pictures taken with conventional lens; **G** and **H**, crops from overlapping portions of input pictures taken with telecentric lens.

5. Benefits: Remote Curation

What advantages does the whole-drawer imaging of insect collections offer to curatorial staff? Firstly, these techniques are not limited to insect specimens but can be used for a variety of museum collections, for example, geological and paleontological (Molineux 2013). In many cases

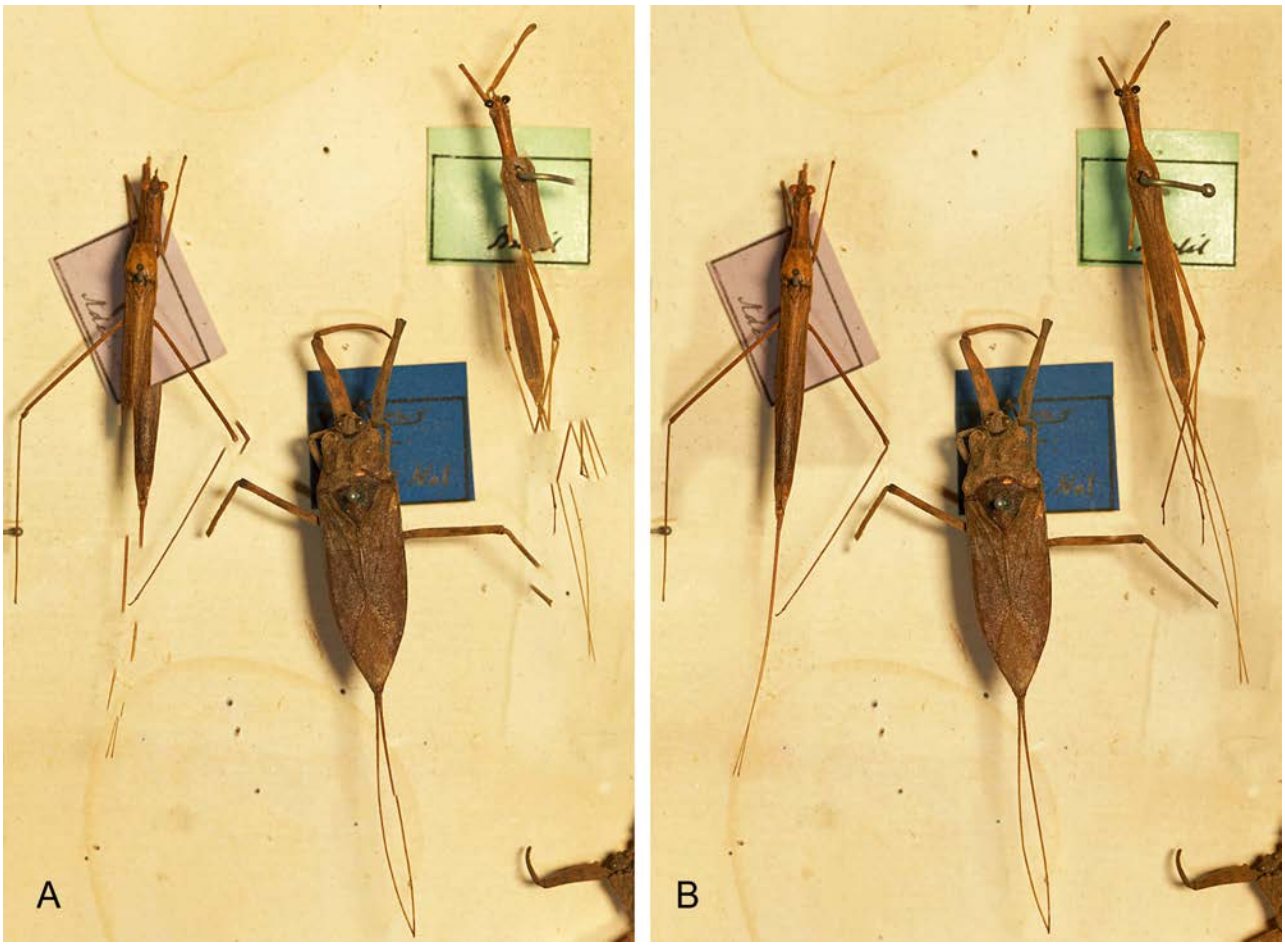

Figure 5: Examples of stitching artefacts of large insect specimens, which extend over several input images, caused by the use of conventional lenses and suboptimal software algorithms: **A**, unedited image; **B**, image after editing.

whole-drawer images can provide sufficient morphological information to researchers, such that they do not need to contact curatorial staff to arrange the loan of specimens or visits to the museum. The reduced need for loans and handling of the specimens/movement of the drawers can reduce the risk of damage to the specimens. Specimens that are in a poor state of preservation may lose crucial diagnostic information by repeated handling and movement, and so become considerably less useful to researchers. Therefore, digitization may have a positive effect on the conservation of specimens. Of course, it is important that the original specimens remain carefully conserved and not neglected in favour of the digital images, as although these constitute useful supplementary material, they cannot replace the original insect specimens.

For intensively curated scientific collections, where label information has already been digitized and made available online, whole-drawer images can help researchers firstly to make sure that the material in question is correctly identified, and secondly to verify that the preservation state of species and their number is satisfactory for research purposes and justifies the expenses associated with a loan or visit (Balke *et al.* 2013). This is not only relevant to type material, but to any specimens present in the museum collections. However, whole-drawer imaging technologies will be of most importance for collections that do not have any information about their specimens currently available online, for those including unidentified material and also for collections curated by those without sufficient expert knowledge to answer very specific taxonomic questions. Consequently, the technology has been of particular importance for the Germar Collection.

Whole-drawer images of Germar's collection of *Hemiptera* and *Homoptera* has made it much easier for the curators, who are not trained entomologists, to distribute information about its holdings to the scientific community. Digital images also break linguistic barriers, which were and still are serious obstacles for international collaboration. In some cases, curators are being completely bypassed. This does not mean that they are no longer needed, instead, it is possible for them to focus on conservation duties, actual loans and research. But the most important benefit that whole-drawer imaging offers to the scientific community is that it allows uncatalogued collections to be studied again.

6. Future Perspectives

6.1 Affordability and Flexibility

Any whole-drawer imaging system would benefit from the availability of affordable object-space telecentric lenses designed for APS-C and 135 format sensors; currently these are around 4–10 times more expensive than regular macro lenses. Flexibility of the system, for example, availability of a range of affordable telecentric lenses

with different fields of view and working distances, would allow users to design their own photographic systems depending on the desired final quality and resolution of images, magnification and speed of the process. Flexible whole-drawer imaging systems would also broaden their potential customer base and enable expansion of their use into other fields of collections management.

6.2 Digital Display of Thematic Collections

Museums are often rightfully criticized for showing only a very small part of their collections to the public. Most museums have considerably more exhibition-worthy material than they can ever display. All museums are limited in space and human resources, necessitating serious restriction of what they can display and how often they can rotate the exhibitions. Some museums now offer virtual tours of their exhibitions as a sort of preview in order to attract potential visitors, and some show their most valuable or unique specimens in three-dimensional online images. Many museums have also been building up their online collections websites to cover all of their objects, including those not on public display. Whole-drawer imaging can help to speed up this process, enabling visitors to observe large parts of the collection that are kept in storage. These digital records need not be aimed exclusively at researchers.

Many natural history museums house so-called 'personal' insect collections, which were purchased from private collectors in the past. Often, their scientific value may not be high, but they are already organized in such a way that they are ready for exhibition, with all specimens carefully arranged and labels attached below the specimen and fully legible. Such collections are rarely used for research and are often the least utilized part of museum heritage. They do not have high scientific value because they often include relatively common species, and sometimes do not have detailed information about where and when specimens were collected. On the other hand, they have great aesthetic and educational value, and can attract museum visitors (**Figure 6A-C**). There are also specifically designed 'teaching collections', created not just to display specimens, but also to provide extensive biological information about them (**Figure 6D-F**). For example, collections of insects, such as pests of agricultural plants, showing different developmental stages of the organism, its plant host and symptoms of damage, accompanied with a detailed description of species identification features and its impact on the crop. Images of such collections can be digitized relatively quickly and used for educational purposes.

There are two possible ways to display digital images of such collections: physically on the museum premises, or online. Displaying the virtual collections in the museum obviously requires allocation of some physical space and installation of high-resolution touchscreen monitors. This can suitably complement existing museum displays and provide more interactive feedback for visitors. Online display of such virtual exhibitions, on the other hand, can reach a larger audience and be more interactive, for example, by incorporating social media, and has the advantage that this does not require any physical space in the museum itself.

7. Conclusions

Recently developed whole-drawer imaging technologies can provide great research opportunities for scientists around the world and change the management of natural history collections. These technologies also have great but unexplored potential for education and public outreach. We believe that future development of whole-drawer imaging technologies should focus not only on increasing the speed and effectiveness of the digitization process, but also on its affordability to a broader customer base, expansion to other types of museum collection, emphasis on its usefulness for teaching and popularization of science through the creation of interactive virtual exhibitions.

Glossary

Focus stacking: image processing technique that combines in-focus (sharp) areas from several input images, which were taken at different but partially overlapping focus intervals. The resulting image shows greater depth of focus than any of the original input images.

Hemiptera: scientific term used to define an order (taxonomic rank) of insects, which includes, among others, plant bugs, stink bugs, water bugs and so on. These are 'true bugs'; part of their first pair of wings is toughened.

Homoptera: scientific term used to define an order (taxonomic rank) of insects, which includes, among others, cicadas, planthoppers, leafhoppers and so on. *Homoptera* lack the hard area on the first pair of wings characteristic of *Hemiptera*.

Machine vision camera: camera that is used for imaging-based automatic inspection or analysis, for example in quality control, analysis (measuring and sorting), guidance of automatic equipment and so on.

Object-space telecentric lens: lens which has its entrance pupil at infinity and produces an orthographic projection of the subject, where the magnification of the image is the same for objects located at different distances from the lens.

Orthographic projection: a way of representing a three-dimensional object in two dimensions where all the projection lines are at right angle to the projection plane.

Piezo-frame module: Hasselblad's patented device, which uses a piezoelectric actuator to move the imaging sensor inside the camera along the XY axis at pre-determined distances.

Stitching: a process of combining several images with overlapping fields of view to produce one larger image.

Stitching artefacts: imperfections in the stitching process most commonly caused by the differences in the overlapping areas between two combined images.

Type material: a specimen or a group of specimens of an organism (taxon), to which the scientific name of that organism is formally attached by the act of designation in the officially published description of this taxon.

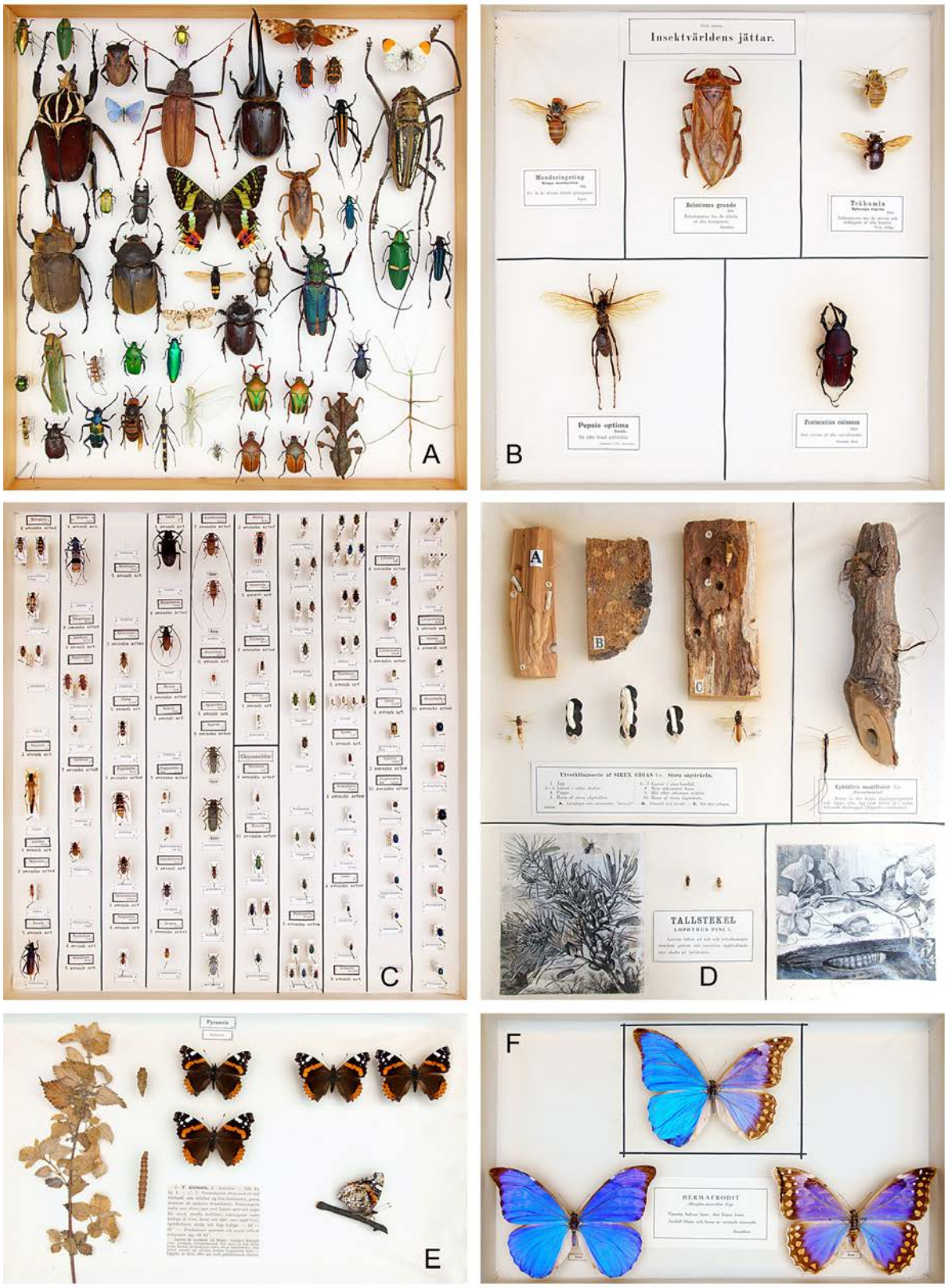

Figure 6: Examples of insect drawers with limited scientific but high aesthetic and educational potential: **A**, drawer with unlabelled large and colourful, mostly tropical insects showing a variety of shapes and sizes of different insect species; **B**, one of the drawers from the series '*Giants of the Insect World*', showing the largest species from several different insect taxa; **C**, one of the drawers from the series on Swedish beetles, with each genus represented by one species, and the number of Swedish species mentioned on special labels; **D**, one of the drawers from the series dedicated to *Hymenoptera*, showing complete development cycle for one of the species; **E**, one of the drawers from a series on common butterflies, showing the different life stages and host plant of the Red Admiral; **F**, drawer showing hermaphrodite specimen alongside of normal female and male specimens of the Morpho butterfly.

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