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METHODS ARTICLE

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A simple methodology for creating and applying replicable, photograph-accurate coloration to 3D-printed models for animal behavior studies

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Abstract

Researchers often use artificial models of animals to elicit and study behavior. Until recently, these models were typically handcrafted; however, 3D-printing technology has been adopted by researchers looking to create accurate and consistent animal models from scans of living animals, taxidermies, or existing models. While 3D-printing techniques create models with accurate and repeatable shape and size, applying coloration to these models is still typically achieved with traditional methods, such as painting by hand. These approaches can be time-consuming and require high levels of artistic skill, creating a barrier to producing realistic models, especially when more than one model or standardized coloration is required. Here, we present a simple workflow to avoid these issues by creating a photograph-accurate paper "skin" that can be glued onto 3D-printed animal models to provide surface coloration. We have used this methodology to create avian models for several experiments, and found that it can create highly detailed and standardized models with minimal training and is independent of artistic skill. Additionally, this method allows the files needed to accurately recreate models to be shared digitally with other researchers, further enhancing repeatability in the field.

KEYWORDS

animal decoy, artificial stimuli, dummy animals, experimental models, paper models, papercraft

1 | INTRODUCTION

Artificial animal models (often called "dummies" or "decoys") are widely used in field and laboratory studies as a substitute for live animals or taxidermic mounts. This practice has been employed for at least 70 years (Tinbergen & Perdeck, 1951), but in the last two decades has begun to incorporate 3D-printing to generate models. Models are advantageous as they have fewer ethical concerns than live animals, and mitigate any risk of damage to taxidermy specimens that would otherwise be deployed in experiments. Broadly, 3D-printing creates custom models through computer-controlled layering of material, based on digital designs (Gross et al., 2014). Other reviews have already addressed the developing role of 3D printing in the ecological sciences (Behm et al., 2018; Walker & Humphries, 2019), but to date, there are few recommendations for a simple, repeatable process that can generate shape and color-accurate models. We seek to rectify this, so that researchers using artificial stimuli can create highly detailed models in an easy and replicable manner.

While 3D-printing presents a way to create a standardized artificial model, at present, the most economical method involves printing with single-color mediums, providing the shape but not the surface coloration of the natural stimulus (demonstrated in Figure 1a). Full-color 3D-printing is possible but can be expensive both in-house and externally, and it is difficult to estimate when this niche market may be available and affordable to customers seeking limited, custom print runs, or how accurately individual printers will be able to replicate color.

Instead, a common approach when creating models is to first create a monochrome base that has the correct size and shape, which is then hand-painted. This approach has been used in a wide range of taxa, including invertebrates (Cianca et al., 2013), fish (Ziegelbecker et al., 2020), frogs (Gardner et al., 2021), lizards (Senior et al., 2021), birds (Biagolini-Jr & Perrella, 2020), and eggs (Hauber, 2020; Igic et al., 2015). However, painting by hand reduces reproducibility, as it introduces individual variation to each model, creating less standardized stimuli. Additional time is also required to paint highly detailed models, so experiments that require numerous stimuli typically need to trade-off detail with the number of stimuli required, thus producing more "generalised" or stylised models. For example, researchers may simplify model preparation workload by painting broad body parts in flat colors, removing depth or fine details, and thereby reducing similarity between the real animal and artificial model. Finally, the quality of a painted model is dependent on artistic skill, a trait that varies between researchers. Even if painted models are simplified in their paint scheme, they remain difficult to share or recreate in a way that allows a repeat of previous experimental conditions, limiting their potential to be replicated both within and between studies.

The variation that hand-painting and similar methods introduce into stimuli is a limitation for the use of models as a tool for researching animal behavior, as this variance between stimuli may impact response to models. Additionally, there is a risk when using simplified artificial stimuli that observed animal responses may fail to generalize to natural stimuli, limiting the insight that can be gained from model presentations (Lahti, 2015). This is particularly true given that researchers often do not ground-truth their models relative to natural stimuli, and as such cannot assess the degree to which responses to models vary from responses elicited by natural responses. While some studies demonstrate that their models elicit the same response as natural stimuli, such as Ruberto et al. (2017) demonstrating artificial and real conspecifics elicit the same response from zebrafish (*Danio rerio*), in general this step is rarely employed. Additionally, while a single model might be proved equivalent to a natural stimulus in one experiment, without a way to replicate the model other researchers are unable to benefit from this work. Moreover, replication is one of the key areas that behavioral research needs to improve on (Schnitzer & Carson, 2016), and unless models can be recreated this is difficult to achieve. What is needed, therefore, is an alternative to hand-painting models that is more replicable and can be shared between researchers. This is particularly true for studies that aim to examine behavior toward species based on difficult-to-recreate visual cues. While some animals can be reasonably replicated using traditional techniques, such as using colored plasticine to replicate snakes (Brodie III, 1993), studies that require models of visually complex species (such as birds with mottled plumage) to answer questions about mate attraction or individual recognition, for example, may benefit from a more standardized method.

"Papercraft" (or "paper modelling") is a process for creating paper models from a printed template by cutting out and combining individual pieces (Haenselmann & Effelsberg, 2012). Papercraft has been used as a quick and inexpensive method to prototype items or architecture (Xue et al., 2010), and software exists to create papercraft templates from digital models (digital representations of three-dimensional objects). Because paper-based models are only as strong as the paper they are constructed with, they are typically relatively weak and not useful as a substitute for animals in experiments, except for animals such as moths or butterflies (Arias et al., 2020; Dell'Aglio et al., 2016). However, papercraft could be used for the same purpose as hand-painting; to provide surface coloration for a stronger base, such as a 3D-printed model. Combining papercraft and 3D-printing therefore allows for models that are physical strong, easy to replace or repair, contain more standardized

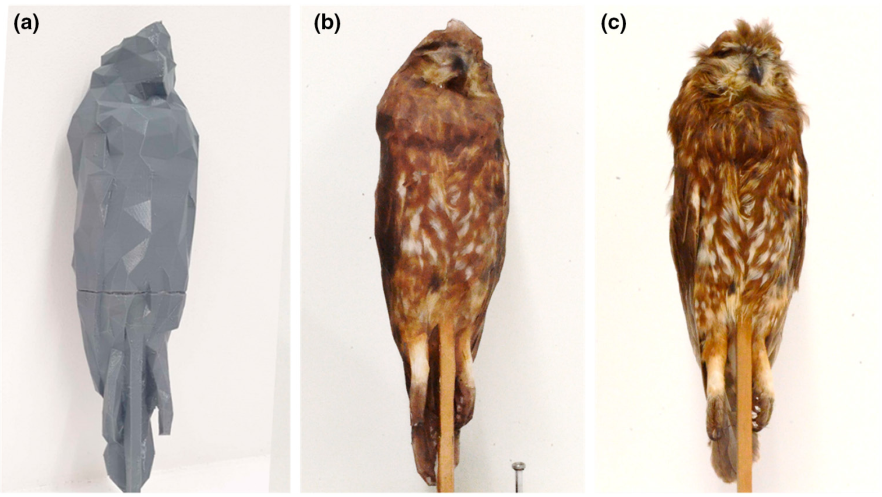

FIGURE 1 (a) An uncolored 3D-printed model Southern Boobook. (Ninox boobook), (b) a 3D-printed model Southern Boobook with a paper "texture" attached to provide surface coloration, and (c) the taxidermized Southern Boobook used to create the 3D-printed model and texture.

surface detail than models painted by hand, and can be shared and recreated inexpensively.

We used this combination of 3D-printed models and papercraft templates to create life-like avian models to study conspecific recognition and response to predators and competitors in Noisy Miners (*Manorina melanocephala*) (Mesken, 2021). Briefly, we created models of a range of avian species (more than 25 models total across eight different species), in perched or standing postures, usually but not always with wings folded. The models varied in size, posture, and color/pattern/detail. The models were used to elicit a response from wild birds in the field and were found to be suitable for these conditions. We found that this method allowed us to create models with greater detail than would have been practical using traditional methods, in a reasonable (for our purposes) time frame. Scanning a taxidermic mount to a digital model, setting up the papercraft template, and 3D-printing the model took roughly 4–6 h of "active" work (time actively working on the task, not including computer processing or printing time), and gluing the papercraft to the 3D-printed model took on average 2 h for a model similar in size and shape to the one in Figure 1, which decreased with practice. However, note that the four-to-six hours active work to prepare the digital model is only required once per species to create as many copies of the model as desired, and can be further reduced if the digital model has been published previously or can be outsourced to a third party. Our models were found to elicit responses that were not significantly different to responses elicited by taxidermic mounts from Noisy Miners (where it was possible to test this).

Here, we describe our workflow for preparing papercraft templates as an auxiliary to 3D-printed models, and for combining the two to create detailed, standardized animal models. This method removes many of the limitations of painting 3D-prints and offers an alternative to expensive full-color 3D-printing. While 3D-printed models are common substitutes for animal stimuli, to our knowledge, there are no prior examples of papercraft templates being combined with 3D-priting to create artificial models for studying animal behavior. We therefore present this technique as a means for allowing increased repeatability within and between studies, and so that researchers can also use standardized models that are independent of external factors such as access to skilled artists.

2 | MATERIALS AND METHODS

This method for creating papercraft templates will often need to take place alongside the creation of a digital model from an existing stimulus (in our case, a taxidermic mount). To help ensure a quality output, we describe a process for creating both papercraft template and 3D-print, although other sources, such as Schtickzelle et al. (2020), have described the process of producing 3D-prints previously. The method described here also assumes access to equipment such as a camera and both a 3D- and inkjet/laser-printer. While this requires some initial buy-in (entry-level 3D printers can be purchased for $300–500 USD), the running costs are comparable creating and coloring a model by hand. We found the total cost of consumables (PLA 3D-printer filament, paper, and ink) to create a model like Figure 1 was around $2 USD.

To avoid being bogged down in equipment- or software-specific details, we name the tools we use, but describe the process in general terms. Figure 2 outlines the methodology as a whole.

2.1 | Creating a digital model using photogrammetry

The first step is to obtain a digital model of the specimen/object that you wish to replicate. There are several ways to do this, and the most appropriate will vary according to availability and researcher needs. The most convenient option would be to use an existing model, either from a previous study or from an online site such as Thingiverse (https://www.thingiverse.com) or cgtrader (https://www.cgtrader.com); however, models of most species are not yet available online. Models can also be created in digital modeling software or created by "scanning" an existing object. For this technique, any method of arriving at a digital model is acceptable, as long as the quality meets the researcher's needs and the digital model contains information about the surface color of the object.

Here, we used photogrammetry, which requires little initial buy-in and has been used previously to create models of animal specimens (Irschick et al., 2020; Mungee & Athreya, 2020; Muñoz-Muñoz et al., 2016). Broadly, photogrammetry is a process for creating 3D models from photographs of a subject taken from different angles. The photographs are analyzed to identify key points in each photograph, and to compare key points between photographs. When points are found to be shared between photographs, the relative distance between points is calculated to allow points to be plotted relative to each other in 3D space, and from there used to recreate a digital model of the subject. (Bot et al., 2019). From a practical perspective, this simplifies to three steps; (1) a subject is obtained and positioned so that it can be photographed; (2) images are obtained by photographing the subject from a wide range of angles, either by moving a camera around the subject, rotating the subject in front of a camera, or by using multiple cameras; and (3) the photographs are imported into software that is then used to reconstruct the subject from the photographs. There are many photogrammetry programs available; we used Agisoft Metashape (version 1.5.2, Agisoft LLC), other examples include Autodesk Recap (Autodesk Inc), and Meshroom (AliceVision). We found that approximately 300 photographs per subject was adequate to reconstruct the subject digitally, but this will depend on how complex the subjects physical shape is. Rather than move the camera, we rotated the subjects in front of a stationary camera, as seen in Figure 3, similar to the method described by Medina et al. (2020). It is preferable to use a subject that has a similar posture to the desired model, as this minimizes the amount of editing required.

It should be noted the color and detail captured at this stage will provide the basis for the papercraft template that is developed later,

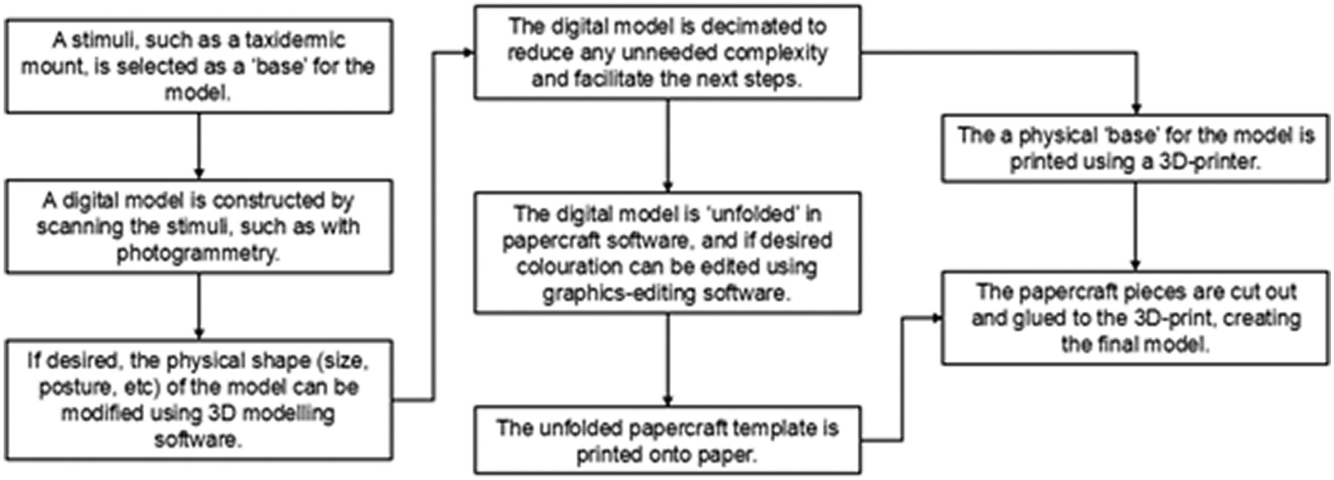

FIGURE 2 A flowchart describing our process for creating models. In situations where a digital model of the desired stimuli already exists, the first two steps are unnecessary.

FIGURE 3 A taxidermized Southern Boobook (Ninox boobook) being photographed to create a digital model that can be 3D-printed and used to create a printed 'texture'. The model was rotated by gently turning the clamp and paper sheet between photographs. We used a paper sheet covered in colored triangles, as we found this improved the alignment of the photographs.

so care should be taken to avoid artifacts. For example, if the photographs are taken under hued lighting, these color and tone differences become part of the digital texture of the model. To avoid this, subjects should be captured under diffuse, neutral white lighting to minimize shadows and show the subject's natural coloration. If very accurate colors are required, such as when investigating very subtle variation in visual signals, it may be necessary to calibrate for the camera and printer settings (a task beyond the scope of this paper), but we found that photographing stimuli in a room lit by multiple bright white LED fluorescent ceiling lights was sufficient for color accuracy like that seen in Figure 1 (see Figure 3 for an example of our lighting).

2.2 | Preparing the digital model for print

While photogrammetry can produce highly detailed models, these models often require some postcapture processing before printing to optimize output. Photogrammetry output may need to be scaled to the correct size, have any digital artifacts removed from the model, and be orientated as required for final printing. While not all photogrammetry software provides this functionality, other 3D-modeling software such as Blender (Blender Foundation) can edit digital models if required.

Before creating a papercraft template, we highly recommended the model is "decimated." Decimating reduces the number of faces used to describe the shape of a digital model, with the aim of reducing file size and complexity. While decimating reduces the amount of complexity used to describe the shape of the model (Kobbelt et al., 1998; Veneziano et al., 2018), the overall shape will be largely unaffected unless decimation reaches very high levels (Angheluţă & Rădvan, 2017). As an example, Figure 4 shows a Southern Boobook (*Ninox boobook*) with and without "surface texture" (the coloration applied to the raw shape of the model), decimated to 10% of its original complexity while maintaining overall shape.

Reducing the number of faces in the model (as in Figure 4b–c) at this stage has the advantage of making it easier to create the papercraft template, in the same way that a jigsaw puzzle with fewer, larger pieces is easier to assemble than one with many smaller pieces. The degree of decimation that can be applied will vary according to the project aims and requirements.

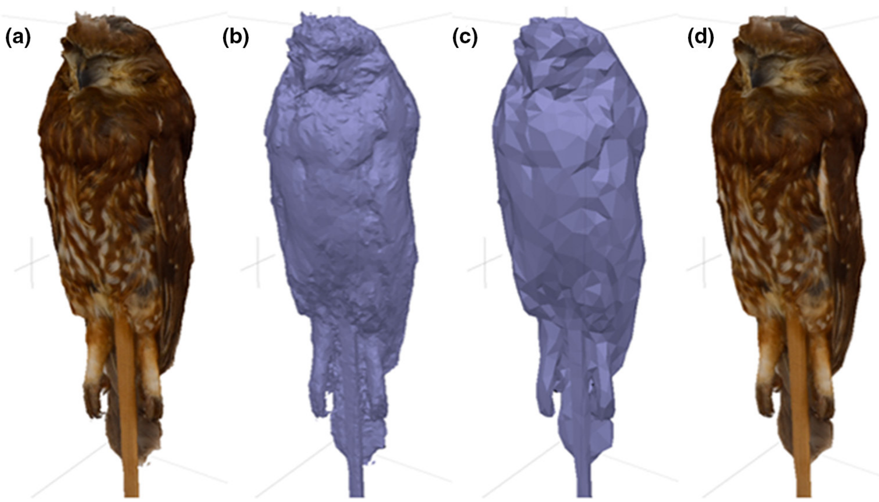

FIGURE 4 Decimation of a digital model representing a Southern Boobook (*Ninox boobook*). (a) The original model (textured), with 20,000 faces, (b) the original model (untextured), with 20,000 faces, (c) the decimated model (untextured) with 2000 faces, and (d) the decimated model (textured), with 2000 faces. Note that (a) and (d) are visually very similar, despite a 90% reduction in the number of faces.

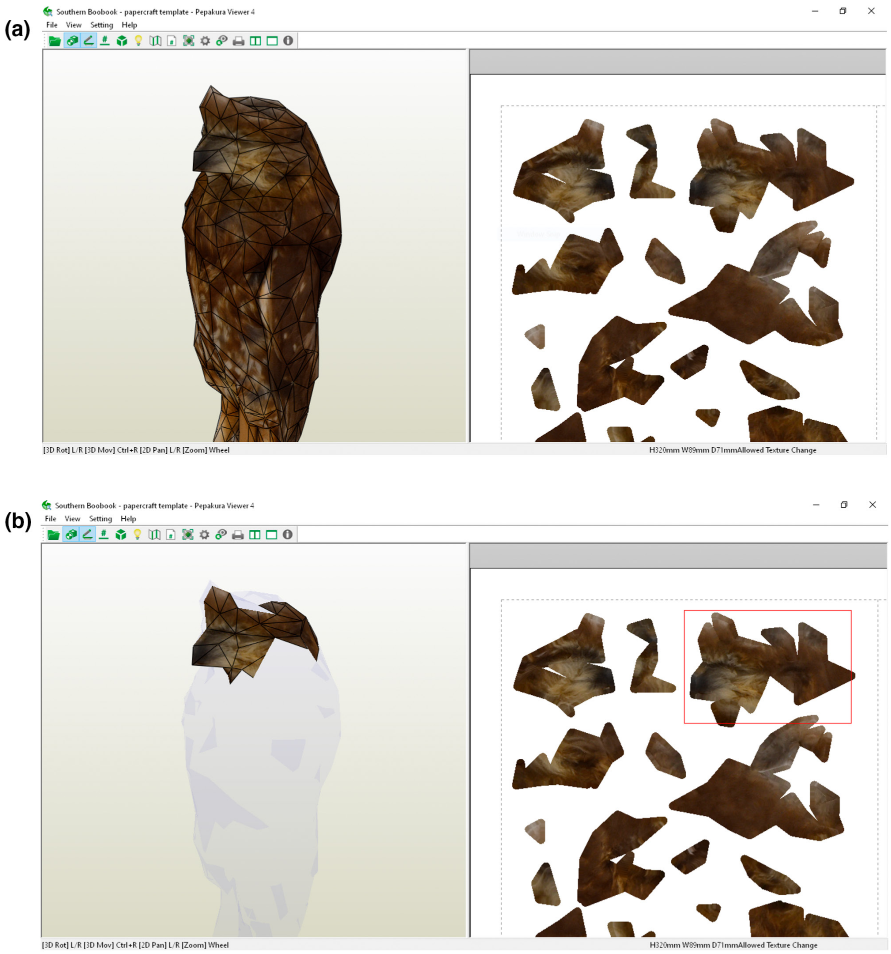

FIGURE 5 A demonstration of how Pepakura Viewer facilitates attaching printed "texture" to 3D-printed models. In (a) the software shows digital model on the left and a series of papercraft pieces on the right, with no specific piece selected. In (b) a specific papercraft piece has been selected, causing the software to demonstrate its position on the model.

Preprinting is also a good stage to edit the digital model, if its color or shape need to be modified by the researcher. There are a range of characteristics that can be altered. For example, the posture and size of the model (both as a whole and of individual features) can be modified using 3D-modeling software to investigate how changing these features affects response or to prepare the model for display, such as ensuring the model is naturally positioned on a perch. There are a range of 3D-modeling software available that will enable the physical shape of the digital model to be transformed; Blender, mentioned above, is a free and open-source software that the authors have used previously for this purpose (Mesken, 2021). Coloration can also be modified by editing the texture of the model. It is possible to change the hue, brightness, and contrast of the whole or individual features of a digital model, and also to change the size and shape of colored features such as spots, patches, or stripes (to change the visibility of courtship or warning signals and thereby investigate their role, for example). There is also many software capable of digital color manipulation; Blender has the capability to edit model color, and GIMP (GIMP Development Team, https://www.gimp.org) is another free, open-source image-manipulation program that can be used for these purposes.

Once the digital model has been prepared, it can be exported from the software. Most papercraft software will require an .OBJ file containing both the geometry and the texture data, while 3D-printing often uses a .STL file, which contains only shape data.

2.3 | Preparing the papercraft template

Creating a papercraft template requires the use of speciality software. We used Pepakura Designer (version 4.2.0, Tama Software Ltd.), but other software exists. These programs unfold digital models into a series of flat pieces; to represent a complex three-dimensional shape on a two-dimensional plane, the model is often divided into smaller pieces. Most software facilitates automated division of pieces; however, we found that some initial user input created pieces that were more intuitive to cut out and apply. Papercraft software assumes that pieces are going to be joined together without internal support, so introduces "fold-lines" and "edge flaps" to help fold and attach pieces. These are not required if the papercraft is to be glued onto a 3D model, and leave a visual artefact that reduces realism, so these fold-lines and edge flaps should be removed prior to printing (in Pepakura Designer, this is achieved by reducing these lines to 0% opacity, most other papercraft software will have a similar feature). It is also helpful to be able to overlap edges when gluing pieces to the model to avoid any gaps; we applied a 1.5 mm edge overlap when printing templates in Pepakura Designer (again, most papercraft software will have a similar feature).

2.4 | Printing and assembling the physical model

The digital model can be 3D-printed using any 3D-printer and compatible software; we used a da Vinci Pro 1.0 printer (XYZ Printing) and associated software to print our models using 1.75 mm-diameter gray PLA filament. There are numerous alternative printers and materials that can be used, or 3D-printing can be outsourced. It should be noted that for large models, it may be necessary to split the model into pieces. This can be done in any modeling software, and the final model is glued together after printing.

The papercraft template can be saved as a .PDF file and printed on any printer that satisfies the level of color and detail accuracy needed by the researcher. We used a Canon Pro 10S printer with associated Canon ink cartridges (Canon Inc), and printed onto Reflex Bright White Premium paper (Reflex GmbH & Co.). Once printed, the process of cutting out the pieces and gluing them to the 3D-print is straightforward; as each piece is cut out, use the papercraft software to illustrate its location on the model (as shown in Figure 5), and glue it together using a glue appropriate for both paper and your 3D-print material—we used Elmer's Glue-All glue (Elmer's Products). The files needed to recreate this model using the described technique are available as Appendix S1.

3 | DISCUSSION

Herein, we describe a cost-effective, accessible method for creating a papercraft template to glue onto 3D-prints, which allows researchers with limited specialist equipment and training to produce highly accurate models. This approach offers an alternative to hand-painting that does not introduce intermodel variation, and does not rely on artistic skill. Furthermore, it also allows researchers to include their models in publications as Appendix S1, thereby allowing others to replicate the models from other studies and enhancing tests of repeatability that are required in many fields (Kelly, 2006; Parker et al., 2016).

This method should provide a base that covers any applications in behavioral research across a range of fields that further allows customization as needed. For example, some animals can see and react to colors outside the range replicated with a traditional camera and printer or paints, such as ultraviolet light (Cuthill et al., 2000); in these cases, additional work will be required to achieve color accuracy, such as coating-specific areas of the model with specialized reflectants or printing with specialized inks (Stoddard et al., 2019).

However, it should be noted that papercraft has some limitations in its application. For instance, this method requires an initial digital or physical model, such as the taxidermic mount used here, to create the 3D-print and papercraft. It is possible to manipulate the color, size, and shape of the model digitally before printing, and therefore, it is not necessary to have an exact replica of the stimuli you wish to create. For example, if a taxidermic mount is postured in the "wrong" posture for researcher needs, this can be corrected in the digital model before printing. If the coloration a specimen has degraded, such as from being stored in ethanol, this can also be restored provided there is enough coloration left to work from. However, creating an entirely new, realistically detailed model or coloration can be quite difficult, which is why it is preferable to work from an initial stimulus that resembles the desired model as much as possible.

Additionally, while "simple" shapes such as flat surfaces or smooth curves, such as eggs and unruffled fur or plumage, are relatively easy to 3D-print and apply a paper cover onto, this method becomes more difficult and time-consuming to use with animals that have highly complex shapes, or long, thin features such as spines or individual protruding feathers. This constraint makes this method more appropriate for species (or other stimuli) with relatively flat or smooth shapes—for example, an egg, a snake, or a perched raptor could be made quite well with this technique as their surfaces are not particularly complex, while an organism such as a sea urchin would be very difficult due to its complex form. This constraint is shared with many traditional mediums; it is more difficult to make organisms with very complex shapes out of sculpted clay, for example.

Very small animals are also more difficult to create, as accurately applying papercraft to a small 3D-print can be challenging.

A paper-based approach as outlined here is poorly suited to environments where paper would rapidly becoming discolored, such as around wet/moist or excessively dusty or dirty conditions. This can be partially remedied using additional coatings (readily available options include microglaze, waterproof sprays, or mod podge) to protect the model from discoloration in many field conditions, but for experiments where models are likely to be submerged or left exposed to weather for extended periods, it may not be possible to avoid the paper becoming discolored. We have primarily used models in brief (<30 min) exposures to wild birds in a natural woodland setting, with models used up to 16 times over the course of an experiment. We found the paper covering to be durable and retain coloration under these circumstances. Further measures, such as covering models during transport or ensuring hands are clean before handling, could be implemented to increase model longevity if needed.

Finally, it should be stated that this technique is not always needed to replicate color, and is likely excessive in situations where it is very easy to replicate natural coloration by hand-painting or other methods. This is essentially a method for replacing one potentially time-consuming task (applying coloration to models by hand) with an alternative (gluing paper cutouts to a model). Whether this is more efficient will depend on the experiment's need for detailed coloration, the researcher's efficiency in applying that detailed coloration using traditional methods (which generally decreases with increased color pattern complexity), and the researcher's efficiency in applying the paper cutouts to the model (which generally decreases with increased physical complexity of a model). This method can also create highly standardized models, which would recommend its use where this is important and otherwise difficult to achieve. In general, we suggest that this method would be most useful for studies that aim to vary single aspects of stimuli, such as studies of visual signaling or camouflage, or when comparing responses to visually similar species.

The methodology described here is intended as a single tool in a toolbox for creating artificial models. We have found this method cost-effective, accessible to those without artistic skill, to allow high control over individual model parameters, and the resulting models easy to replicate. By applying this method, we hope that researchers can create and share highly detailed, easily replicable models.

AUTHOR CONTRIBUTIONS

Jarrod Mesken: Conceptualization; methodology; writing – original draft; writing – review and editing. **Christa Beckmann:** Conceptualization; writing – review and editing. **Paul McDonald:** Conceptualization; writing – review and editing.

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CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

All files used to create the Southern Boobook model described in this article are available in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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