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REVIEW

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Design considerations and techniques for constructing video stimuli

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Abstract Techniques for constructing video playback stimuli fall into five categories. The first three involve manipulating video sequences: (1) edited video is a temporal rearrangement of raw footage, (2) processed video applies global filtering algorithms to edited video, and (3) frame-manipulated video involves manually altering individual frames. The last two, (4) exemplar-based animation and (5) parameter-based animation, are synthetic models derived from visual parameters based on a single exemplar and sample data, respectively. Image-based approaches are straightforward to apply and preserve fine spatiotemporal detail. Synthetic stimuli are desirable when a large number of manipulations are called for and to ensure individual stimuli reflect population characteristics.

Key words Animation · Video playback · Visual signals

Introduction

This volume, and the symposium that produced it (the Lisbon Video Playback Workshop), represent a kind of coming of age for video playback. The technique has matured conceptually, from demonstrations of one species or another responding to video stimuli, through debates about the validity of the approach, to the point where video playback has taken its place among the established tools of animal behaviour. The increased use of video playback has been fostered by the development of sophisticated, accessible technology for generating and manipulating video sequences. As recently as the early 1990s, many potential stimuli were inaccessible to researchers because of technological limitations or prohibitive cost. It is now possible to create a wide range of stimuli within the constraints of the output system.

Given these constraints, which are discussed elsewhere in this issue (Cuthill et al. 2000; Fleishman and Endler 2000; Oliveira et al. 2000; Zeil 2000), researchers are faced with the decision of how stimuli should be constructed. Video playback strives to present experimental animals with biologically realistic stimuli. Whether they are designed to reconstruct whole phenotypes or to dissect the salient features of a signal, these stimuli should be designed with an eye to the natural conditions in which animals normally process visual information, and to the perceptual biology of receivers (Oliveira et al. 2000). The playback stimuli we use should also represent an adequate sample of signal variation (McGregor 2000, in this issue), and trait manipulations should be precise and readily accomplished. The different approaches to video playback often represent trade-offs among these goals.

Edited video

The most straightforward video stimulus is simply edited footage of animals performing the desired behaviours (e.g. Evans and Marler 1991; Macedonia and Stamps 1994; Macedonia et al. 1994; McQuoid and Galef 1993; Roster et al. 1995; Baker et al. 1996; Rosenthal et al. 1996; Clark et al. 1997; Balshine-Earn and Lotem 1998; Landmann et al. 1999). The experimenter can manipulate the order and arrangement of segments of video so as to obtain the appropriate repertoire. Current computer technology has made very precise editing accessible to most workers. Powerful video-digitising software and hardware are now available, and a variety of non-linear editing software applications allows the experimenter to easily rearrange and repeat video clips in any order. Each sequence, of course, represents only a single stimulus exemplar, the individual originally recorded. The ease of

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Supplementary material. Data on making synthetic animations and video films are available on Springer Verlag's server at http://link.springer.de/link/service/journals/10211/index.htm

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manipulating sequences, however, reduces the burden of constructing stimuli from multiple exemplar animals.

Since only the temporal sequence is being manipulated, however, this technique is only useful for a limited subset of experiments. The morphology of the stimulus animal, and scene parameters such as illumination and background characteristics, are fixed when the original video is taken. It is therefore critical that the original footage be acquired with these parameters in mind. The most appropriate approach is probably to record an animal in its natural habitat, although natural background cues may provide misleading information about apparent size when viewed on the flat surface of the monitor (Zeil 2000). If animals are filmed in the laboratory, illumination and background characteristics should approximate those encountered in nature. While video output systems will generally fail to reproduce typical ambient light intensities or spectral characteristics (Fleishman and Endler 2000), stimuli can be designed to approximate the natural direction of illumination and the relative contrast between an animal and its background. Many studies using edited-video stimuli fail to report these critical scene parameters altogether (Rosenthal 1999).

A final, rather obvious caveat about edited video is that it is important to maintain continuity between sequences. If, for example, we videotape an animal performing a series of three agonistic displays and excise the middle one, we should avoid an abrupt shift in the transition from the first to the third. Such discontinuities can have potentially confounding effects, since subjects are effectively being presented with a novel visual stimulus. Ensuring continuity can involve considerable effort in obtaining raw footage and matching the desired sequences. An easy solution, feasible in many cases, is to have the animal in the stimulus sequence move offscreen between successive behaviours.

One use for edited video is as a straightforward assay for whether the animals being studied will respond to video at all; if animals fail to behave meaningfully towards edited video, it is unlikely that they will respond to more sophisticated manipulations. The stimulus need not even be videotaped; subjects can be presented with real-time monitor output of a live exemplar (Gonçalves et al. 2000).

Processed video

Edited video can be modified via global filters that affect all or part of a stimulus sequence. This can be done with dedicated hardware during playback [e.g. varying colour output, Rowland et al. 1995a,b, Bolyard and Rowland 1996; chroma-keying (global modification of a selected colour), McDonald et al. 1995, McKinnon 1995; changing playback speed, Rowland 1995] or with filtering algorithms applied to digitised video. Standard non-linear editing packages, such as Adobe Premiere, contain a wide variety of filtering routines, including scaling, masks, and colour substitution. Such techniques can be extremely useful, since one can readily change the parameter of interest throughout the scene. Because they act globally on individual frames, though, filters can introduce undesired artefacts; for example, a scaling algorithm will not only scale the exemplar animal but also objects in the background. When judiciously applied, though, filters are a powerful means of extending the edited-video approach.

Frame-manipulated video

Perhaps the most common type of video stimulus in the literature is the result of a tedious process in which a video sequence is digitised, individual frames are imported into a bitmap-editing program, and each is individually altered by the researcher or, more likely, his or her unfortunate red-eyed assistant. Until recently, this was the only feasible way of manipulating most morphological and contrast traits, and numerous studies have used this approach to manipulate behaviour and morphology independent of one another (e.g. Clark and Uetz 1992, 1993; Evans et al. 1993; McClintock and Uetz 1996; Uetz et al. 1996; Allen and Nicoletto 1997; Rosenthal and Evans 1998; Clark and Stephenson 1999; Körner et al. 1999; Nicoletto and Kodric-Brown 1999). At 25 frames/s for PAL and 30 frames/s for NTSC, this represents a tedious and time-intensive process even for brief sequences. The return for effort is low: each procedure results in only a single parameter manipulation in a single individual. Since this technique uses edited video as the source material, the same caveats apply about ensuring that appropriate parameters are set during filming.

Frame-manipulated video is prone to producing a number of artefacts. Aliasing effects between a manipulated trait and background colour can often be difficult to avoid, and erasing morphological traits and replacing them with background can create spatial discontinuities. Moreover, one is manipulating two-dimensional projections of animals performing behaviours in three dimensions. It is thus difficult to alter individual aspects of morphology with precision. For example, if a courtship display involves motion towards and away from the receiver, and one wants to enlarge a morphological trait, the trait would have to be scaled according to distance from the camera. This is particularly difficult for structures such as fins and feathers, which have a tendency to deform when moving rapidly.

Despite these concerns, frame manipulation is a proven technique that can preserve much of the spatiotemporal complexity of an original video sequence while allowing broad flexibility in morphological manipulations. It is particularly appropriate for creating stimuli of short duration where motion is confined to the plane of the screen.

Exemplar-based animation

Synthetic animation differs from the above approaches in an important conceptual way. The above techniques all deal with video footage as such, a two-dimensional pro-

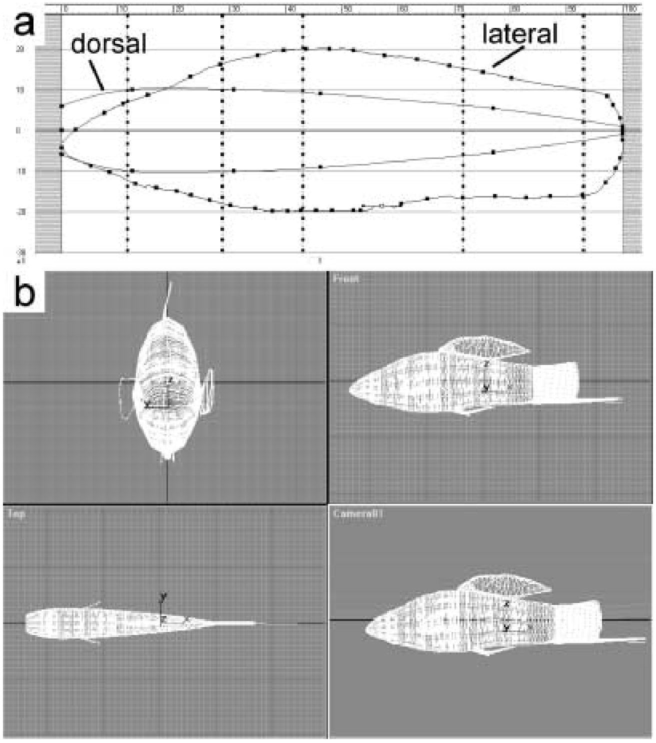

Fig. 1a,b Screen captures from 3D Studio Max animation software. **a** Lateral and dorsal outlines used in lofting the three-dimensional shape of a male pygmy swordtail, *Xiphophorus nigrensis*. The lateral and dorsal traces are scaled according to ellipses (*dashed lines*) placed at intervals along the outlines. Truncating the rostrum of the dorsal outline is necessary to achieve tapering of the snout. **b** Three-dimensional wireframe model lofted from curves in (**a**)

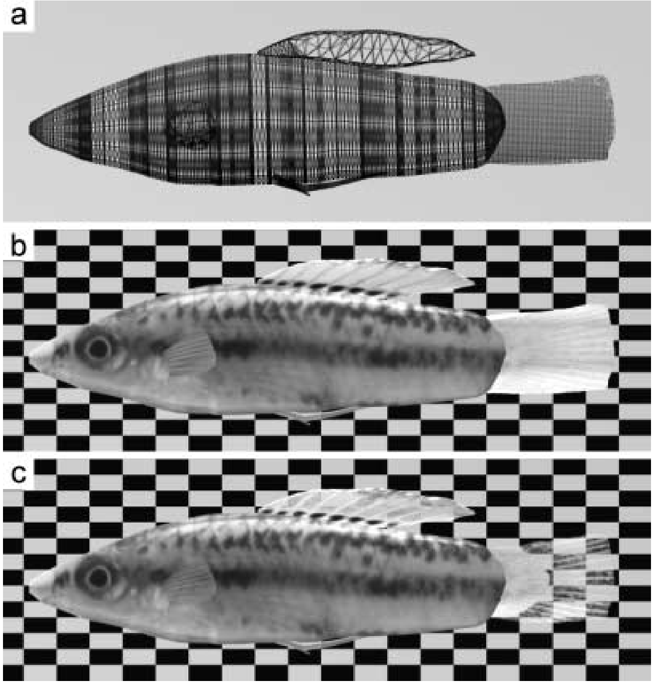

Fig. 2a–c Applying material properties to an object. **a** Wireframe model with (**b**) diffuse colour maps and (**c**) opacity maps added

jection of a three-dimensional scene. With edited video, the operational unit is the frame; with frame-manipulated video and certain types of processed video, it is the individual pixel in a frame. With animation, one is instead manipulating individual parameters in a model of the three-dimensional world. Since these parameters are what we can quantify on real animals, and since these are usually what we wish to vary in our stimuli, synthetic stimuli offer a more direct route to the aspects of a signal we are interested in. This is a relatively novel technique in animal behaviour (but see McKinnon and McPhail 1996; Künzler and Bakker 1998; Bakker et al. 1999); therefore the approach is presented here in some detail. This particular methodology is the author's, working on fishes, and using the animation program 3D Studio Max version 1.0 (Kinetix). There is a broad diversity of techniques, and both form and the kinematics of motion in legged animals call for a substantially different approach to modelling. This section describes using data from a single exemplar animal as the basis for a synthetic stimulus.

The first step is to construct a three-dimensional static model of the animal. Serial slices of preserved animals (Künzler and Bakker 1999) or a three-dimensional scan (K. Heubel and I. Schlupp, personal communication) can provide a detailed basis for the model. An alternative is simply to trace an outline from a digitised photograph of an individual and measure the individual's thickness into the plane of the photograph. A process called "lofting", in which a series of cross-sections are interpolated along a complex path, is then used to integrate the thickness measures with the outline (Fig. 1). Thin structures like fins can effectively be modelled as nearly two-dimensional sheets – this information can be extracted from a photograph alone.

To the static model, we then apply maps specifying colour (see Fleishman and Endler 2000 for a discussion of colour reproduction constraints), texture, specular properties, and opacity. These maps can be digital images of our exemplar animal; for diaphanous fins, for example, two maps are employed: a diffuse-colour map, essentially an unmodified photograph of the fin; and an opacity map, which specifies the degree of transparency at each point on the object (Fig. 2).

One important consideration in constructing the static model is its complexity. Objects with more facets take longer to process, but many facets are required to smoothly render body deformations.

We can now specify environmental parameters – background characteristics, lighting, and filtering. For an animation of a courting swordtail, I used an averaged sample of backgrounds in the field. The primary light source, from directly overhead, was designed to mimic the sun at noon, casting parallel rays. A series of dimmer, omnidirectional lights, designed to mimic scattering and reflection from the substrate and suspended particles in the water, was arrayed around the model fish (Fig. 3). It is also possible to give attenuation properties to the medium, so that contrast between cues is rendered as a

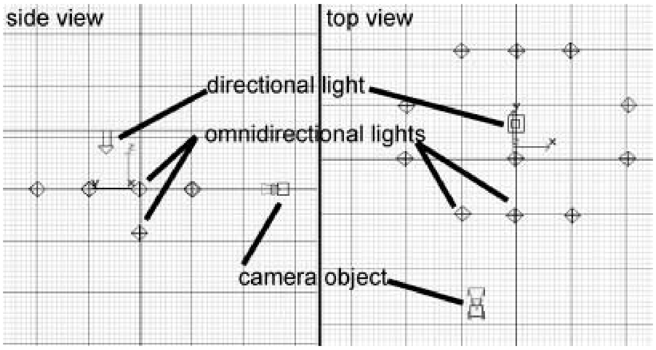

Fig. 3 Directional and omnidirectional lights used in the scene. The camera object, which determines the perspective view as rendered, is at bottom

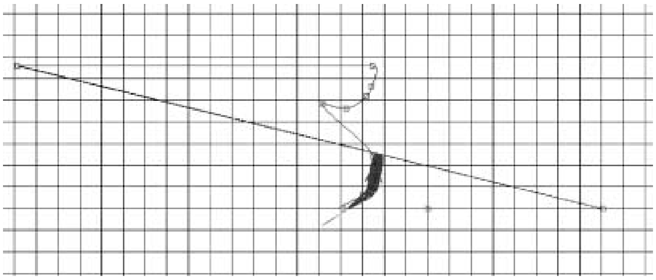

Fig. 4 Trajectory (*curve*) of the courtship display of male *X. nigrensis*. *Squares* represent "key frames", points in time where motion parameters are specified explicitly. From the perspective of the camera object, the fish appears to swim onscreen, perform the display, and swim offscreen. The *straight diagonal line* indicates the offscreen return of the fish to its original position

function of distance to the observer. Environmental parameters can also be dynamic, allowing one to simulate effects such as the flickering properties of underwater light (Loew and McFarland 1990).

Applying exemplar motion to a static model is straightforward. One can use either of two approaches. The first is to use image-analysis software to measure the position, orientation, and deformation properties of the live animal and apply this information to the model (Fig. 4). Alternatively, one can use rotoscoping, in which the model is superimposed on live footage of the animal. Small adjustments are made to motion parameters over small time intervals, allowing the animated model to match the movements of the live exemplar.

The final step is to specify an observer "camera" such that the animal is life-sized on the output monitor (Zeil 2000); the position of the camera can change over time, providing different perspective views of the behaviour being tested.

All the aforementioned parameters can be manipulated according to the experimenter's aims – for example, different bitmaps, representing a variety of surfaces assigned to an animal, can be substituted to create stimuli with different markings, scale can be adjusted in all or a subset of axes, appendages can be enlarged or shortened, and behavioural components can be removed, repeated, or modified. The great advantage of synthetic animations is that once the initial parameters are specified, they can be changed with a few keystrokes; removing an ornament from a stimulus takes approximately 30 s, versus several weeks with a frame-manipulated stimulus.

The danger with synthetic animations is that the experimenter will fail to model properly key aspects of the stimuli. With footage-based techniques, the information captured on video is essentially preserved throughout the process. With synthetic animations, salient aspects of motion, form, or illumination effects may be missing or erroneously represented. Due to the inherent limitations of video, however, these differences are probably not severe: the spatial and temporal resolution of video is sufficiently low that loss of fine detail in a synthetic stimulus is minimal relative to a videotaped animal.

Parameter-based animation

Exemplar-based animation allows precise, quantitative manipulation of stimuli yet limits our ability to generalise about stimulus properties, since features are based on a single individual. With parameter-based animation, stimuli are constructed based on population samples or theoretical models. One can thus construct an array of stimuli that vary according to the distribution of traits in the population, for example, one standard deviation above and below the mean. In addition to incorporating variation into stimuli, this technique is valuable in that stimulus parameters can be estimated from data collected in the field, an important consideration since laboratory-reared animals often differ substantially from their wild counterparts in both behaviour and morphology – especially in size and coloration. The process of constructing these animations is the same as that used for exemplar-based stimuli; the difference lies in the data that are used to make the model.

Form parameters – the three-dimensional shape of the body and appendages – are estimated from detailed measurements of animals, and/or from a sample of body outlines or serial slices from different individuals, averaged using image-processing software. The material properties of the animal can be modelled from reflectance or averaged image data from a sample. Environmental parameters can also be estimated from sample data, by using image-processing tools or spectral data to model background and lighting characteristics. While these will not be represented accurately by a video monitor (Fleishman and Endler 2000), they do provide a first approximation of appropriate light conditions within the constraints of the output system.

Estimation of behavioural parameters can be complex and time consuming. Motor patterns that are periodic and confined to a single plane, such as male displays in anoline lizards (Fleishman 1992), are particularly tractable for analysis; position data can be recorded from a single perspective view. For patterns that involve motion in three dimensions, two synchronised stereoscopic or orthogonal views are necessary to recover quantitative spatial information. Since there are qualitative and quantitative differences in swordtail courtship behaviour between the laboratory and the field, I estimated position (as a function of body length) and orientation based on the movement of both the fish and the camera relative to background cues, from videotapes taken in the field. While this method does not yield the same precise measures as would two-camera analysis in the laboratory, it is much better at estimating the gross parameters of courtship: display rate, for example, is significantly faster in the field than in the laboratory (G.G.R. and M. J. Ryan, unpublished data).

In practice, many synthetic animations will be compromises between exemplar- and parameter-based techniques; for example, I used sample data to model form, motion, body deformation, and background, but I used a digitised photograph of a single male for material properties of the fish surface to preserve fine spatial detail. Given the enormous number of parameters that can be specified for an animation, such compromises are unavoidable. A complete representation of the visual information provided by a given animal – even the comparatively small subset that can be meaningfully represented on video – is virtually unattainable. Investigators must decide which traits are salient based on knowledge of sensory biology and behavioural responses to natural variation in visual parameters.

Pseudoreplication (McGregor 2000) represents another concern when deciding between exemplar- and parameter-based techniques. As an example, let us say we are interested in the effect that the size of a male ornament has on female preference within a particular population of fishes. One approach is to use a set of randomly selected exemplars, let us say 5, taken from the population and perform the desired trait manipulation in each. The appropriate hypothesis to test here is the effect of the trait manipulation within the context of that random sample. The alternative approach is to sample a suite of traits in the population (from, say, 20 individuals) and use the mean value for each trait to construct a parameter-based model. The hypothesis to test is now the effect of the trait manipulation in the context of a suite of traits of mean value for the population. Which of these comes closer to testing the more general hypothesis, that is, that female preference depends on the value of the trait across all males in the population? In the context of the general hypothesis of a trait effect across males, the effective sample size in the exemplar-based approach is the number of exemplars used (McGregor 2000), in this case 5. In the parameter-based approach, is the effective sample size 1 (the number of exemplars used) or 20 (the number of individuals sampled to estimate mean parameters)? As emphasised by McGregor (2000), it is critical to define clearly the hypothesis being tested, that is, preference for traits in the context of a random sample of exemplars versus preferences for traits in the context of mean values for other traits. A researcher interested in addressing how a trait interacts with population variation in other traits may favour the exemplar-based approach, whereas one desiring to measure sexual selection in the context of mean phenotypic values may prefer parameter-based animation.

The decision of which method to use must further be informed by the organism's natural history and perceptual biology, and by the particular question being addressed. If fine spatial details are a limiting factor, as appears to be the case in chickens (D'Eath and Dawkins 1996), an entirely parameter-based approach is impractical. If only temporal parameters (e.g. the presence or absence of certain behaviours) are to be manipulated, and if a small number of manipulations is to be made, edited video of animals in a natural context is generally the best approach. Stimulus preparation is fairly rapid, and variation can be sampled by simply using multiple exemplars (e.g. Rosenthal et al. 1996). This technique minimises artefacts and loss of information. A similar argument can be made for processed video, with the caveat that care must be taken not to introduce extraneous artefacts in processing. Researchers planning to use a large array of stimuli should consider synthetic animations, where precise manipulations can be made rapidly.

The trade-off in biological realism between synthetic and edited video is not an obvious one. Spatial cues are likely to be better preserved in edited video, especially given the effort required in modelling fine details. Most synthetic animations presented to animals to date omit many aspects of complex body movements that may be meaningful to receivers. It may be difficult, however, to obtain quality footage of a particular behaviour, particularly if behaviour changes from the field to the laboratory. It would be valuable to conduct direct comparisons of subject responses to different video approaches to the same stimulus. Synthetic animations can be used to test explicitly the effect on receiver response of complex motor patterns, allowing the researcher to identify which cues are required to adequately model behaviour for a particular study organism.

A recurring theme of recent work on video playback, and of this volume in particular, is the need for more rigor in studies using the approach. In early video-playback studies, emphasis was placed on coaxing existing editing technology to perform interesting stimulus manipulation. This technology has ceased to place restrictions on video studies, which are now and for the foreseeable future constrained by limitations in the output system. We now have access to techniques that give us the power to manipulate almost every conceivable visual parameter. How (or whether) video techniques are to be used depends on (1) which subset of these parameters is salient to experimental subjects; (2) how data on these parameters can be collected from animals in a biologically realistic context; and (3) whether and how these parameters are represented in the video output that a subject sees. Addressing these questions forces us to examine rigorously the perceptual biology and natural history of the study organism.

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