Supplementary Material: Revealing Information by Averaging

1 Averaging

Tempocodes can be revealed by averaging. With floating point numbers, contrast reduction of the input image and masking is performed without losing precision. A pixelwise average of the original tempocode video exactly yields the input target image. Smartphones can be used for averaging. The video frames are captured. By placing markers around the video, the projective distortion is removed and the rectified frames are averaged (see the supplementary video). Alternatively, a fixed camera can be used to average by integration and to reveal the target image without making any software operation.

The duration of temporal integration can be controlled with the shutter speed [Allen and Triantaphillidou 2012].

As the shutter speed is decreased for longer temporal integration, the aperture of the camera should be decreased as well in order to avoid exceeding the sensor's holding capacity (Fig. 1). *Exposure value* (EV) is a term used in photography to represent combinations of shutter speed and aperture openness (f-number) in order to obtain a given exposure. Ray [2000] defines *exposure value* as follows:

$$EV = \log_2 \frac{N^2}{t} \tag{1}$$

where N is the relative aperture (f-number) and t is the exposure time. Fig. 1 shows the exposure values for different shutter speeds and aperture values.

The messages hidden in the videos generated by our approach can be revealed by long exposure photography. However, as shown in Fig. 1, EV should be lower than 10 to be able to reveal the hidden image from a tempocode having a duration longer than 1 second. We performed several experiments with a Nikon D5200 camera to find the best *exposure value* EV that maps the dynamic range of the display to the dynamic range of the camera while providing as much flexibility in exposure time as possible. Modern displays have a high luminance range. By setting the screen to the lowest brightness (i.e. $55 \pm 5 cd/m^2$) and the camera ISO to 100, we found an EV value of 5.25 as the limit where all pixels are registered without over-exposing. Then, from in Eq. (2), the required aperture *f-number* for an exposure time t is:

$$N = \sqrt{t \cdot 2^{5.25}} \tag{2}$$

For most photographic lenses, the *f-number* is limited to 32. This allows revealing the hidden image for a duration equal or shorter than 16 seconds. Longer durations can be revealed by placing a neutral density (ND) filter in front of the camera.

Camera and screen gamma. The presented work-flow to create videos incorporating a hidden image assume that display and camera are linear. However, usually displays raise the input signal to the power of γ and the cameras raise the sensor response to the power of $\frac{1}{\gamma}$. We linearize the display by applying to its input a power of $\frac{1}{\gamma}$, called gamma correction, and linearize the camera by applying to its output signal a power of γ before averaging. For sRGB displays, a value of $\gamma = 2.2$ is appropriate. Alternatively a linear camera can be used.

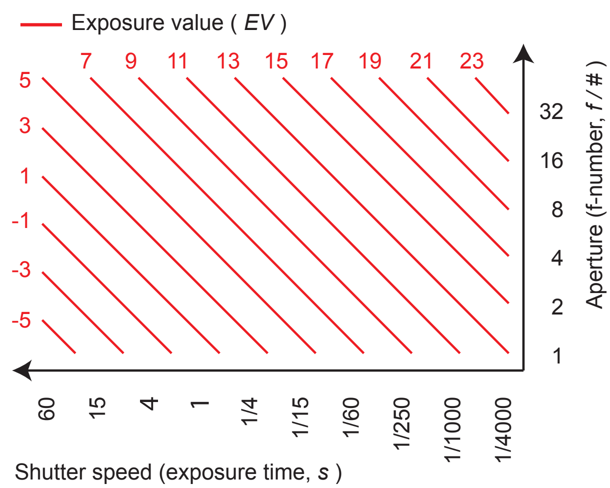

Figure 1: *Exposure values as a function of aperture and shutter speed [Canon 2015].*

2 The effect of multi-band decomposition on masking

The multi-band decomposition contributes significantly to our visual masking method. In Fig. 2, the effect of multi-band decomposition is shown for different contrast reduction factors α and numbers of frequency bands k. The tempocode frames in the second column are generated by using the sinusoid-based composite wave with $k = 7$ frequency bands. The target image is completely hidden in this method when the contrast reduction factor is $\alpha = 0.4$ or lower. However, when there is no frequency band decomposition (i.e. $k = 1$, third column), even for the lowest contrast reduction factors, the target image is visible. Similarly, the tempocodes generated with the temporal dithering function (fourth column) can hide the target image when the contrast reduction factor is $\alpha = 0.4$ or lower. When there is no multi-band decomposition (fifth column), the target remains visible (e.g. especially low contrast details).

References

ALLEN, E., AND TRIANTAPHILLIDOU, S. 2012. *The Manual of Photography and Digital Imaging*. CRC Press.

CANON, 2015. Camera settings: shooting modes.

RAY, S. 2000. Camera exposure determination. In *Manual of Photography*, R. Jacobson, S. Ray, G. G. Attridge, and N. Axford, Eds. Taylor & Francis.

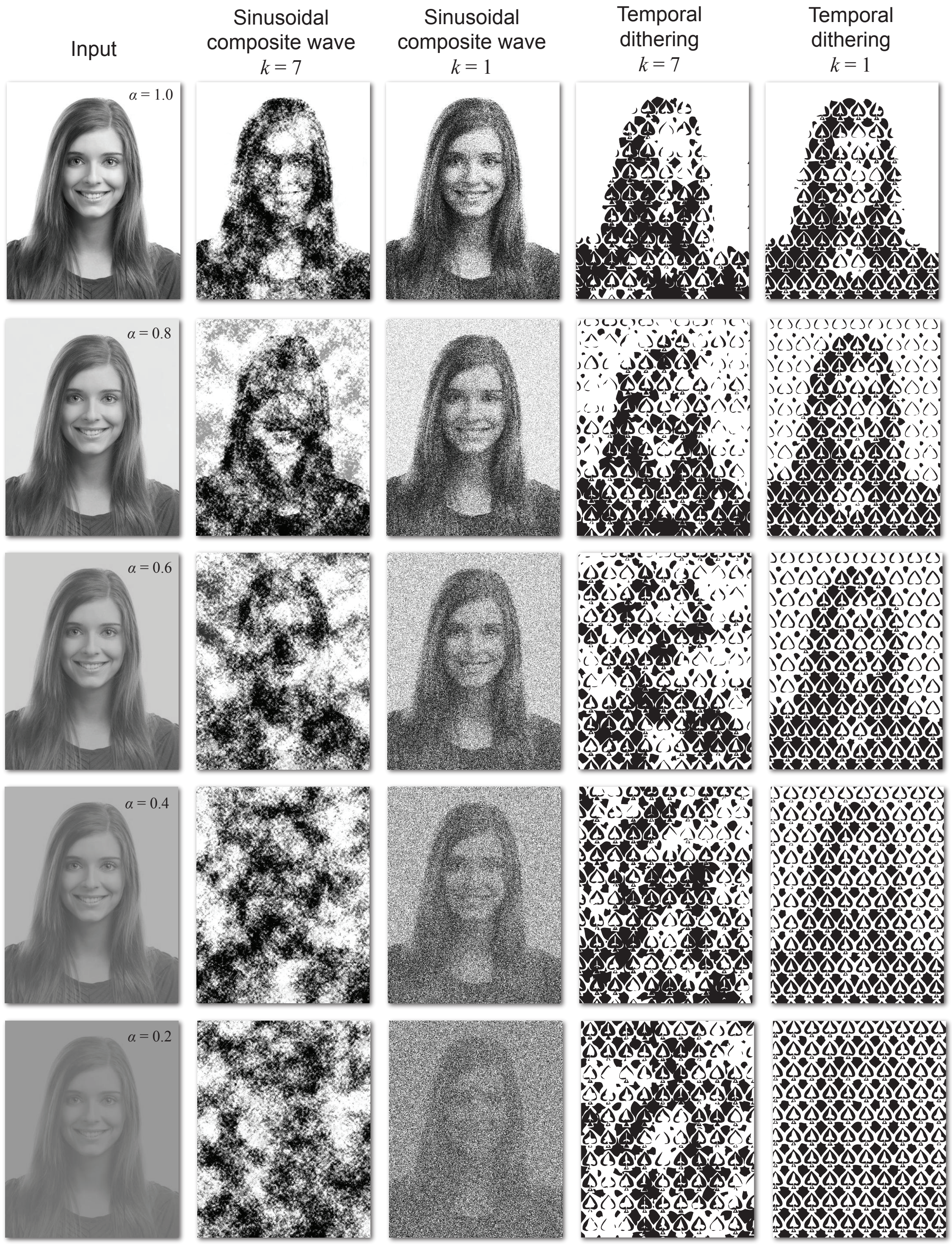

Figure 2: *The effect of multi-band decomposition and contrast reduction on the resulting tempocode frames.*