PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

The Physics of Visual Perception [and Discussion]

F. W. Campbell and D. Marr

Phil. Trans. R. Soc. Lond. B 1980 **290**, 5-9
doi: 10.1098/rstb.1980.0078

Phil. Trans. R. Soc. Lond. B **290**, 5–9 (1980)
Printed in Great Britain

The physics of visual perception

By F. W. Campbell, F.R.S.
The Physiological Laboratory, Cambridge, CB2 3EG, U.K.

By measuring the contrast threshold for gratings of different waveform and spatial frequency, Campbell & Robson suggested in 1968 that there may be 'channels' tuned to different spatial frequencies. By using the technique of adapting to a high contrast grating, it was possible to measure the band-pass characteristics of these channels. Similar techniques were used to establish the orientational tuning of the channels. Reasons are put forward why it is advantageous to organize the visual system in this manner.

Any temporal or spatial stimulus can be characterized by its Fourier transform (Taylor 1965). By varying the contrast and spatial frequency (fineness) of a grating, kept at constant mean luminance, it is possible to measure quantitatively those Fourier components of a visual scene that are available to our eye–brain. This technique, and the results obtained in man and in the cat are described by Campbell & Maffei (1974). The results are summarized in figure 1. (The shaded area is the invisible world of ectoplasm, fairies and ghosts.) How does this approach help us to understand the visual world that we can see (the unshaded area)? Why are we not aware of the undetectable portions of the scene? These problems troubled Helmholtz and Mach (Ratliff 1965).

When we examine a standard optometrist's eye test chart, lines that are too small for us to resolve still seem to be composed of high contrast black letters. Thus, there seems to be some mechanism to ensure contrast constancy, so that as we move about the world, the contrast of objects does not change (Georgeson & Sullivan 1975).

Campbell & Robson (1968) showed that the contrast threshold for gratings with a sinusoidal profile was different from those with a square-wave profile. These observations were extended into the suprathreshold domain by Campbell *et al.* (1978). For gratings with spatial frequency greater than 1 cycle/deg, the square-wave grating is perceived slightly better by a factor of $4/\pi$. If we accept that in this spatial frequency range the visual system performs a quasi-Fourier analysis on the image, this is precisely the expected result, for this is the relative amplitude of the fundamental in a square wave. Indeed, it is difficult to see what other mechanism could account for this finding.

For frequencies less than 1 cycle/deg, the visual system behaves quite differently. At any of these low frequencies, square waves of all spatial frequencies have a constant low (0.25%) contrast threshold. Even at a spatial frequency of 1 cycle per 180° (i.e. a single edge) this remains valid. As the spatial frequency is clearly irrelevant in this instance, it seems that the square wave is detected by virtue of its individual edges rather than as a gestalt grating. Sinusoidal gratings of these low frequencies are greatly attenuated or invisible. Indeed, they can be removed from a square-wave grating, altering its luminance profile dramatically, but without affecting its appearance or detectability. This effect is analogous to the phenomenon of the missing fundamental in audition (Goldstein 1973), and has a neurophysiological interpretation (Maffei *et al.* 1979).

A sinusoidal grating is physically infinitely blurred, while a square wave is infinitely sharp. A sine wave has only a single frequency component in its Fourier spectrum containing all the wave's power. A square wave has, in addition, a shower of higher odd harmonics of linearly

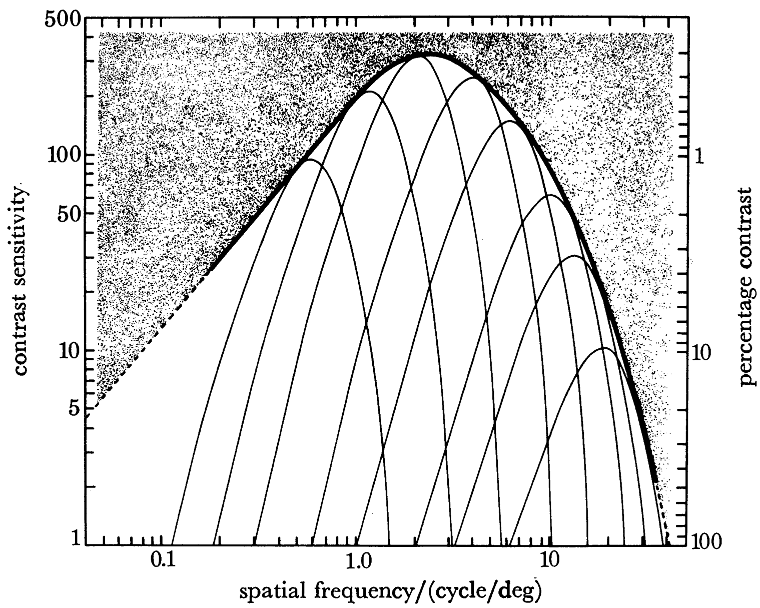

FIGURE 1. The thick curve represents the contrast sensitivity (defined as reciprocal threshold contrast) of the human visual system to a sinusoidal grating, plotted against spatial frequency. The shaded area must always remain invisible to us unless the spatial frequency content of the image is shifted into the visible domain by optical means, such as the microscope. The lighter curves represent channels sensitive to a narrow range of spatial frequencies.

decreasing amplitude. Campbell *et al.* (1978) have shown that low-frequency square gratings are perceived as true square waves, provided that they possess the first few higher harmonics (in appropriate phase). The auditory analogue of this is that the click of a metronome is detected by the neurons tuned to high temporal frequencies. Similar neurons tuned to a band of spatial frequencies approximately one octave wide exist in the visual cortex of the cat (review by Maffei 1978), and the elegant work of De Valois *et al.* (1978) has shown that the monkey visual cortex is similarly organized. Indeed, the important discovery by Hubel & Wiesel (1962) that cells in the visual cortex are sensitive only to a narrow range of stimulus orientations is immediately suggestive of a Fourier analytical process. The existence of channels sensitive to particular bands of spatial frequencies of particular orientation can be demonstrated psychophysically in man by adaptation experiments (review by Braddick *et al.* 1978). Indeed the first evidence for these channels was found psychophysically by Campbell & Robson (1968), who stated that 'a picture emerges of functionally separate mechanisms in the visual nervous system each responding maximally at some particular spatial frequency and hardly at all at spatial frequencies differing by a factor of two. The frequency selectivity of these mechanisms must be determined by integrative processes in the nervous system and they appear to be a first approximation at least, to operate linearly.'

Figure 2 illustrates a picture of a tank that has been analysed by three broad-band channels, respectively sensitive to the low-, medium- and high-frequency components of the original image. An enemy soldier would be most interested in the low-frequency components, and having established that a tank is approaching him, will turn his attention to survival in the undergrowth. The tank troop commander, however, will be most interested in the intermediate frequency components, which reveal the tank type and number, while the sergeant of the maintenance wing will examine the high-frequency components for signs of damage to the trackwork.

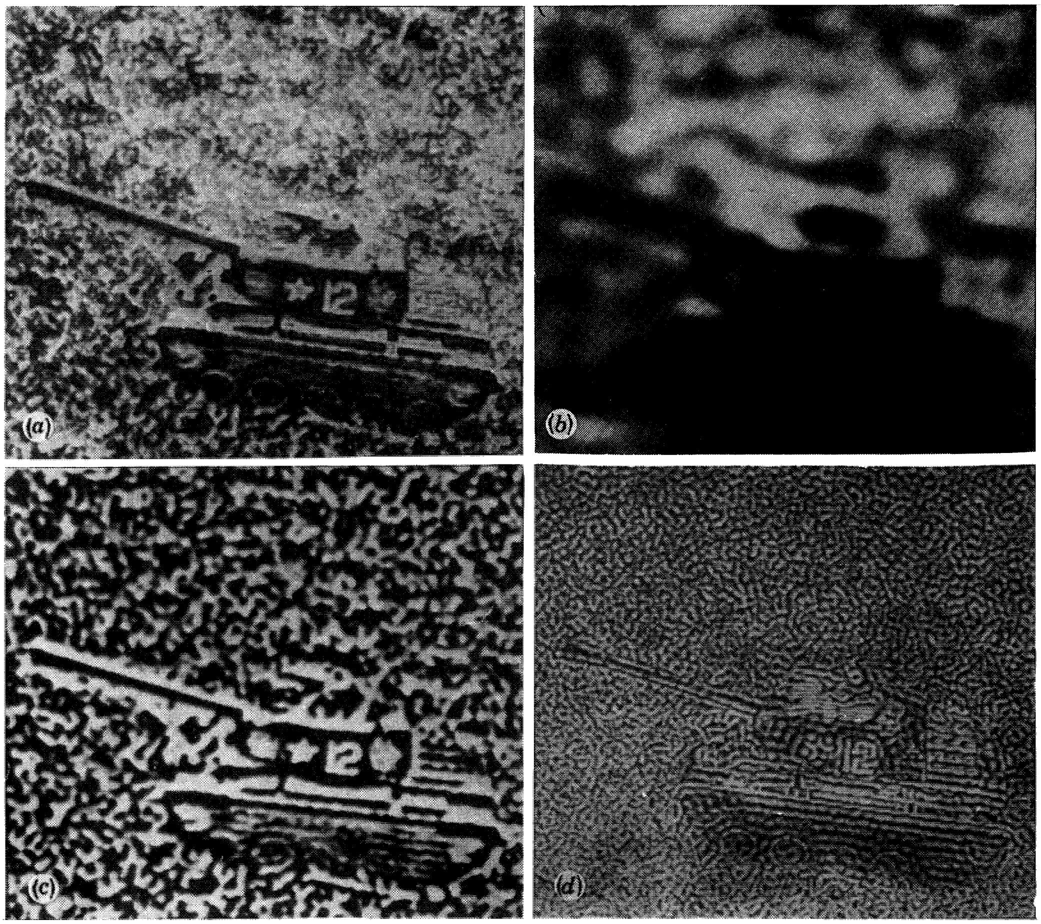

FIGURE 2. (*a*) Original photographic image. (*b*) Same image filtered to pass low spatial frequencies only. (*c*) As (*b*) but with only medium spatial frequencies passed. (*d*) As (*b*) but with only high spatial frequencies passed. (Courtesy of H. C. Andrews.)

The channel model of the visual system raises many interesting questions. For example, Pirenne (1967) has raised an important question when he writes, 'It is a familiar fact that on a moonless night, our vision not only is very blurred, but is also colourless.' If a myope removes his spectacles, high spatial frequencies suffer greater attenuation than do low spatial frequencies. In this case, the visual scene does indeed look very blurred. As the illumination of a scene is reduced, high spatial frequencies are again attenuated much more than low, owing to the shortage of photons available to the visual system, over the eye's integration time (*ca.* 0.1 s), and we might expect Pirenne's prediction of blur to be verified. However, our own observations have

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

led us to the conclusion that at night the visual scene, though devoid of fine detail, is quite definitely not blurred.

A low-frequency sine-wave grating (less than 1 cycle/deg) is always discriminably different from a square-wave grating, even near threshold. This holds to the lowest luminance level. This must mean that some of the higher harmonics of the square wave are being detected. It can also be shown readily that if the eye is defocused by as little as ± 0.5 dioptres, the resulting optical blur can be detected (night myopia).

Owing to photon shortage at these dim illuminations, the neurons that normally respond to high frequencies and which can function under photopic conditions fail to operate, yet we do not notice their absence. The visual system must be aware that these neurons can never fire at low levels, and assumes, if the question arises (as in the perception of an edge or square wave), that the undetectable frequencies are present. Campbell *et al.* (1978) concluded that 'the visual input appears to be analyzed into its Fourier components and if these constitute a square sequence with no above-threshold components missing, then the perception of a square-wave results. This solves the problem, considered by Helmholtz and Mach (Ratliff 1965, p. 265), of why aberrations of the emmetropic eye do not result in all edges appearing blurred. Only when the blurring is great enough to remove independently detectable high frequency components does the blurr become detectable.' Likewise, under scotopic conditions, a square-wave grating always appears to be square because any undetectable missing higher harmonics are not noticed as absent.

Another feature of a moonless night is that the sky is full of stars. It is our opinion that all stars, whether seen in the fovea or on the periphery, look like point sources. This raises an interesting question, for the acuity of vision falls off markedly as eccentricity from the fovea increases. One might expect that when regarding the 'inverted bowl they call the sky' (Fitzgerald 1859) we would see the stars as point sources in the fovea, but as broader and broader smudges as their images fall upon peripheral retinal locations of lower and lower acuity. The fact that we do not suggests that the visual system perceives a small stimulus as a point source, until that stimulus reaches a size great enough for its true size to be signalled by the available channel mechanisms. Thereafter, of course, the true size is perceived, and the objects retain the same apparent size, wherever upon the retina their image falls. The channel system is organized in such a way that where its limited sensitivity intrudes, the stimulus is perceived in its most probable form, be that as a sharp edge or square wave, or as a star.

I acknowledge the help of Mark Lawden in the preparation of this manuscript.

References (Campbell)

Andrews, H. C. 1972 Digital computers and image processing. *Endeavour* **31**, 88–94.

Braddick, O., Campbell, F. W. & Atkinson, J. 1978 Channels in vision: basic aspects. In *Handbook of sensory physiology*, vol. 8, ch. 1, pp. 3–38. Springer-Verlag.

Campbell, F. W. & Maffei, L. 1974 Contrast and spatial frequency. *Scient. Am.* **231** (5), 106–115.

Campbell, F. W. & Robson, J. G. 1968 Application of Fourier analysis to the visibility of gratings. *J. Physiol., Lond.* **197**, 551–566.

Campbell, F. W., Howell, E. R. & Johnstone, J. R. 1978 A comparison of threshold and suprathreshold appearance of gratings with components in the low and high spatial frequency range. *J. Physiol., Lond.* **284**, 193–201.

De Valois, K. K., De Valois, R. L. & Yund, E. W. 1979 Responses of striate cortex cells to grating and checkerboard patterns. *J. Physiol., Lond.* **291**, 483–505.

Fitzgerald, E. 1859 *Rubaiyat of Omar Khayyam.*

Georgeson, M. A. & Sullivan, G. D. 1975 Contrast constancy: deblurring in human vision by spatial frequency channels. *J. Physiol., Lond.* **252**, 627–656.

Goldstein, J. L. 1973 An optimum process theory for the central information of the pitch of complex tones *J. acoust. Soc. Am.* **54**, 1496–1516.
Hubel, D. H. & Wiesel, T. N. 1962 Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J. Physiol., Lond.* **160**, 106–154.
Maffei, L. 1978 Spatial frequency channels: neural mechanisms. In *Handbook of sensory physiology*, vol. 8, ch. 1, pp. 39–66. Springer-Verlag.
Maffei, L., Morrone, C., Pirchio, M. & Sandini, G. 1979 Responses of visual cortical cells to periodic and non-periodic stimuli. *J. Physiol., Lond.* **296**, 27–47.
Pirenne, M. 1967 *Vision and the eye*, p. 36. Chapman & Hall.
Ratliff, F. 1965 *Mach bands: quantitative studies on neural networks in the retina*. San Francisco: Holden-Day.
Taylor, C. A. 1965 *The physics of musical sounds*. London: English Universities Press.

Discussion

D. MARR (*The Artificial Intelligence Laboratory, Cambridge, Massachusetts* 02139, *U.S.A.*). Dr Campbell cannot have it both ways! Either one can inspect his tank independently at different spatial frequencies, in which case one should be able to recognize Abraham Lincoln in L. D. Harmon's coarsely sampled and quantized picture of him, or one should be able to do neither. Since one cannot see Lincoln without effectively blurring the image, presumably one cannot inspect the tank in the way that Dr Campbell suggests. Marr & Hildreth (1979) show how information from the different spatial frequency channels may be combined, by using the spatial coincidence assumption. According to this, when zero-crossings from different channels coincide spatially, they are combined into a descriptive unit (an 'edge') and it is this, not the individual channel outputs, that is available to later processes (see Marr 1976; Marr & Hildreth 1979).

References

Marr, D. 1976 Early processing of visual information. *Phil. Trans. R. Soc. Lond.* B **275**, 483–519.
Marr, D. & Hildreth, E. 1980 Theory of edge detection. *Proc. R. Soc. Lond.* B **207**, 187–217.

F. W. CAMPBELL, F.R.S. A suprathreshold edge situated within a hypercolumn's receptive field contains all spatial frequencies and may excite any and all of the neurons within the hypercolumn that have the correct orientation tuning. Such edges, therefore, would be excellent masking stimuli for all spatial frequencies. In the Lincoln's-head picture it is not surprising that the introduction of spurious sharp edges masks the perception of the pattern defined by medium-to-low spatial frequencies. The edge pattern is foreign to the head and is, therefore, a good mask.

The three filtered images of the tank, however, all arise from the same original picture and cooperate to produce a consistent percept. Certainly, one may pay attention selectively to the information contained in any particular waveband of spatial frequencies, but this does not imply that other wavebands disappear – they do not.

For Lincoln's head the masking edges cannot be made to disappear by feats of concentration, and as the information that they contain is not relevant to the perception of Lincoln they continue to act as a mask.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

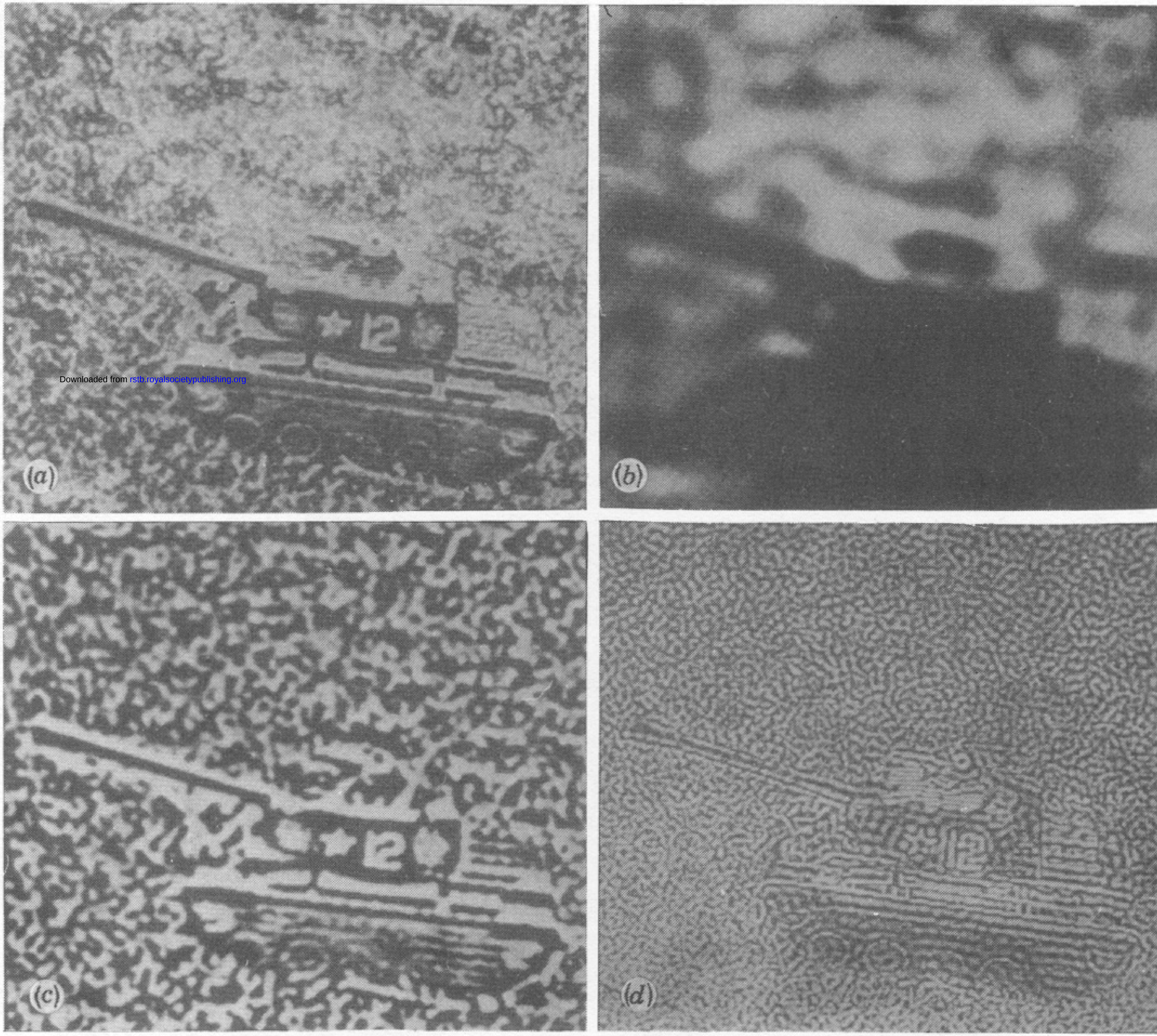

FIGURE 2. (*a*) Original photographic image. (*b*) Same image filtered to pass low spatial frequencies only. (*c*) As (*b*) but with only medium spatial frequencies passed. (*d*) As (*b*) but with only high spatial frequencies passed. (Courtesy of H. C. Andrews.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES