

Contribution to the Theory of Prosthetic Vision

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Abstract

By way of extracellular, electrical stimulation of the visual pathway, the various approaches to vision prosthesis aim to provide crude, patterned vision to sufferers of profound blindness. Common to all approaches is the implantable electrode array and the rendering of phosphenes—the actuated percepts occupying the visual field of the implantee. Thus prosthetic vision may be simulated, and underlying theories as to how to render it efficacious developed. We review the field of simulated prosthetic vision. Further, with retinal prosthesis in mind, we suggest a revised approach—an approach with regard to sampling theory, the vertebrate central visual pathway, and eye movements. The parallel development of prosthetic vision theory, explored via simulation, and bioengineering issues surrounding neurostimulator design and implantation, has bearing on the success of clinical trials by numerous groups in coming years.

Introduction

Charge injected by extracellular, stimulating electrodes, large by comparison to retinal neurons, situated epiretinally has proven efficacious in exciting the visual system of sufferers of retinal degeneration (1, 2). This ability to evoke the perception of discrete light spots—so-called phosphenes—is the cornerstone of on-going attempts by the authors (3) and others (for review, see Zrenner (4)) to provide a retinal prosthetic—a device comprising an intraocularly implantable array of electrodes and analogous to the cochlear implant. The aim is that multiple electrodes (or channels) will make for multifocal, prosthetic vision, a conjectural depiction of which is contained in Figure 1.

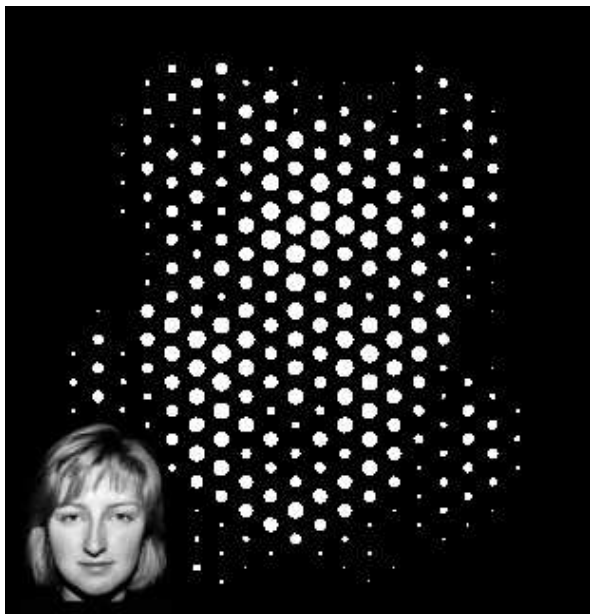


Figure 1—Conjectural depiction of prosthetic vision. The original image (inset) is rendered as phosphenes in the visual field of the implantee via the electrode array. Here, sizes of phosphenes are modulated; the locations of phosphenes correspond to proposed array geometries. The depiction pertains to a 400-channel (400-electrode) device. (Inset image source: Psychology, University of Stirling (5))

The “retinal” approach is similar to the alternate approaches to electronic vision prosthesis (for example, intra-cortical stimulation (6, 7, 8) and optic nerve stimulation (9)) in that large, extracellular electrodes via charge injection seek to render phosphenes in the visual field. Therefore the present discussion of prosthetic vision, to some extent, generalizes to, and indeed draws upon research surrounding, alternate approaches.

In recent work by Humayun *et al.* (10), two subjects underwent implantation of a 4-by-4 array of platinum electrodes affixed to the retina. Via a per-scleral connector, a Clarion cochlear stimulator communicates with the array. Both subjects were able to identify room lights being on or off; one subject responded with 75% accuracy in a four-alternative forced choice “tumbling-L” trial.

Together, this recent development, and the rapid burgeoning of the retinal prosthetics field, suggest it is now timely to reconsider the psychophysics of prosthetic vision; the parallel development of the psychophysics *and* of bioengineering issues will make for better artificial visual outcomes by the

numerous groups likely to undertake clinical trials in coming years.

Numerous auditory neuroprosthesis groups worldwide are in the practice of simulating prosthetic hearing (for example, (11, 12, 13)). Here, multiple bandpass filters (say, 22, in correspondence with 22-channel implantable cochlear devices (14)) are applied to audio stimuli; the reduced signal, approximating the function of a cochlear implant, is presented to the normally hearing via speakers. Such simulations are run with a mind to devising strategies (for example, speech encoding strategies) for processing audio signals so as to improve the artificial sounds administered to cochlear implant recipients. With the retinal prosthesis currently in its infancy it follows that coming years will see the development of prosthetic vision simulators. Here, arrays of phosphenes corresponding with implantable electrode geometries will be presented to the normally seeing with a mind to determining optimal methods of presenting the phosphene image—the prosthetic vision—to the implantee. Indeed, such methodology is the basis for recent work at the authors’ laboratory (15).

There is mounting evidence that while physiological excitation of individual or small groups of retinal neurons is possible, psychophysical phosphene perception may only be possible with large electrodes. It has been suggested that the electrode separation distance (and hence the probable degree of discernment between sites) is likely to be no less than 0.25 mm, the distance at which a 3 dB rise in stimulation threshold is observed in the frog (16). Alternately, it has been shown that (physiological) discernment between electrodes exists with an electrode pitch of 25 μm (17). The differences in resolution between physiological stimulation and psychophysical perception appear to be in stark contrast to one another. Humayan and his co-workers reported that blind human patients could discern 435 μm electrode separation distances, a level of acuity corresponding to crude ambulatory vision (1). A further study has indicated that patterned stimulation could be observed with electrode separations of similar magnitude (2). Accordingly, proposals in the present paper pertain to relatively large electrode geometries—that is, sparsely packed and relatively few channels.

In the following paragraphs, we review the central psychophysics work of Cha *et al.* (18, 19, 20), and the similar approach of Humayun (21), prior to proposing revisions hereto that incorporate sampling theory and image processing. We then discuss the more sophisticated approach of Boyle *et al.* and their “intelligent” algorithms (22, 23), and Eckmiller’s conjectures which consider functional retinal neurology (24).

Quantifying Prosthetic Vision

It is now widely held that implanted electrodes rendering relatively few phosphenes in the visual field are capable of providing *useful* prosthetic vision. Ten years ago this was, for the most part, speculative. Since then, psychophysical studies (pioneered by Cha and co-workers in 1992) have, in effect, pursued the following two questions:

1. Can the prosthetic vision provided by way of relatively few phosphenes be put to *use* by an implant recipient?
2. If so, what parameters, such as number of phosphenes and the extent of the visual field they occupy, will make for *useful* vision?

Cha *et al.* developed an apparatus—a so-called “pixelized vision simulator” (PVS)—in an attempt to empirically quantify electrode densities requisite to efficacious phosphene vision (18). Cha’s portable simulator was set-up as follows. The scene was captured by a head-mounted video camera and displayed on a small television monitor mounted on a pair of goggles worn by the subject. A mask of pinholes was placed over the monitor; the phosphenes presented through each pinhole appeared uniform in intensity and were of fixed size. The masked image was viewed through a lens; by replacing lenses, the extent of the subject’s field of vision occupied by the phosphened image was configurable. The masks used by Cha are reproduced Figure 2.

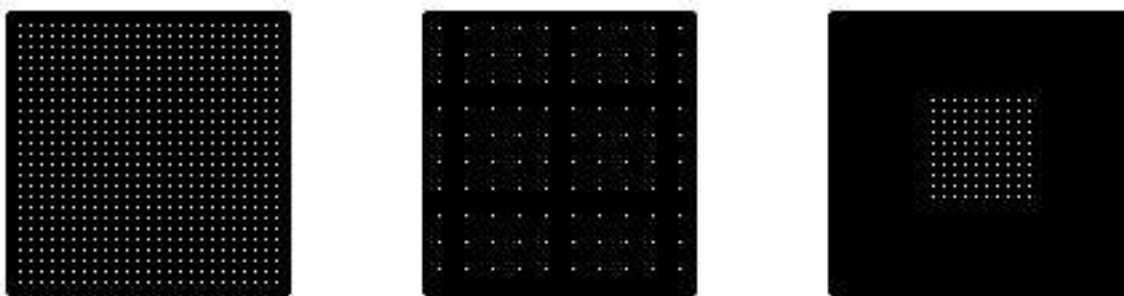


Figure 2—Masks like those used by Cha *et al.*. Subjects effectively viewed the world through an array pinholes—each pinhole rendering a phosphene in the visual field. Cha varied the density of phosphenes (left versus middle), and the extent of the visual field occupied by phosphenes (middle versus right).

As shown, two classes of mask were used: one wherein phosphene density was constant, but dimensions of the phosphene array varied; one wherein phosphene density was variable despite the square array’s dimensions remaining fixed. All masks exhibited a regular rectangular arrangement of phosphenes. By way of this apparatus, Cha *et al.* sought to assess visual acuity (19), reading speed (20), and mobility (18).

In the mobility studies (18), subjects were required to walk through a test course approximately 25-meters long and avoid approximately 20 randomly placed obstacles. The number of obstacle contacts and walking speed were used to quantify mobility. Results found that, with training, walking speed increased and contacts decreased; statistically, logarithm of field of view—by—logarithm of number of pixels rendered was most highly correlated to walking speed (0.915). Control subjects exhibited a walking speed of 0.83 m/s. Cha *et al.* concluded that at least 625 phosphenes need be rendered in central vision, presenting a visual field of approximately 30 degrees, in order to achieve similar walking speeds to those of control subjects. This number was in correspondence with the implantable electrode array in development at the University of Utah at the time.

In visual acuity studies (19), “tumbling E” trials (the letter “E”, white on black, at one of four orthogonal orientations is presented to subjects) were conducted with subjects wearing the PVS. Presentations were made by way of a computer monitor and lasted for 1.5 seconds; a four-alternative forced choice paradigm was employed. Visual acuity was found to vary proportionally with phosphene density. Subjects with normal vision (20/20 Snellen) or thereabouts demonstrated acuity of up to 20/26 with

a 32 phosphene-by-32 phosphene mask. It was calculated that “E” was required to be at least 2.1 phosphenes-by-2.1 phosphenes in size for its orientation to be accurately detectable.

Humayun devised a so-called low vision enhancement system (LVES) so as to extend Cha’s approach to retinal prostheses (21). The approach is similar in that its chief interest is to quantify electrode array parameters (electrode density, overall array dimensions, etc.) which make for useful phosphene vision. In addition, electrode drop-out (some percentage of phosphenes were deactivated) and the effect of reduced gray levels (previously addressed by Boyle *et al.* (22)) are investigated. In sum, it is concluded that a “fair level of visual function” (25) is achievable when a 25-by-25 phosphene grid exhibiting four levels of gray occupies the central 10 degrees of the visual field.

With a mind to rendering prosthetic vision more efficacious, as opposed to quantifying its usefulness, we propose revisions to Cha’s approach. By way of introduction, three issues are discussed here: spatial mosaics for sampling; M- and P-cell pathways in the human visual system; and, the exchange between eye movements and aliasing.

For discrete, spatial sampling, a more dense packing of sample locations is most often desirable. This allows for a higher Nyquist frequency—the frequency above which spectral components of the original signal are misrepresented as lower frequencies in the subsampled signal. For a sampling mosaic that is arrayed, say, hexagonally, its Fourier (frequency) domain representation is too a hexagonal mosaic; as sample locations diverge in space, they converge in the Fourier domain. For a subsampled image, the spectrum of the original image is replicated about each of these locations in the Fourier domain; therefore, as sample locations converge in the Fourier domain, these replicas are more likely to interfere. This interference results in aliasing, which is conveniently defined here as ambiguity in the subsampled image. For more discussion, the reader is referred to the work of Yellott (26). The concept is depicted in Figure 3.

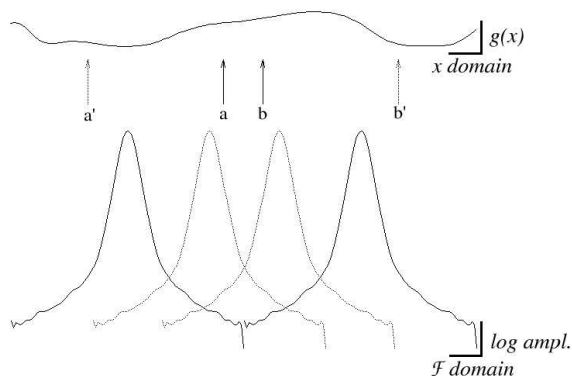


Figure 3—Schematic representation, in one dimension, of the affect of sampling locations on resultant aliasing of the down-sampled signal. As the locations at which continuous signal, $g(x)$, is sampled become more divergent (solid arrows to dotted arrows; a, b to a', b'), the two Fourier spectra of the continuous signal, $g(x)$, (together comprising the spectrum of the down-sampled signal) converge in the Fourier domain (solid spectra to dotted spectra). This convergence leads to interference between spectra, the result of which is aliasing.

Aliasing is undesirable in the subsampled image; it follows that it is advantageous to pack electrodes as densely as possible on the retina. But, how to pack them densely? We propose that electrodes

be arrayed hexagonally such that regions of neural tissue activated by separate electrodes do not interfere. Unless this interference is avoided, eliciting the perception of discrete phosphenes—that is, “multifocal vision”—is unachievable. Geometric results tell us that optimally packed, equisized circles on an unbounded plane form a regular hexagonal mosaic (27). If we assume that approximately circular regions of neural tissue are activated about each electrode—a reasonable assumption in light of the work of Rizzo and co-workers (28) and Humayun and co-workers (29)—then we should array our electrodes in accordance with this geometric result. As compared with regular rectangular mosaics used by Cha and other work hitherto, a regular hexagonal mosaic provides a higher sampling frequency (in space, a vector) and better rotational invariance.

As discussed in previous paragraphs, Cha’s mask involved, effectively, pinholes. In so doing, he employed one of the two obvious solutions to rendering phosphene vision: simply impulsively sample the underlying scene at each phosphene location, as depicted in Figure 4. The other obvious solution is to functionally attach a regional averaging filter to each phosphene such that, in effect, filters tile the underlying scene. A regional averaging filter—typically how an image is pixelized—simply averages the intensity of its receptive field, the *row* \times *column*-area of the image to which it applies:

$$\frac{1}{X \times Y} \sum_0^{X-1} \sum_0^{Y-1} p_{x,y},$$

for pixels, p , in a rectangular region $X \times Y$. The work of Humayun employed regional averaging (21).

The authors posit that neither of these two—impulsive sampling nor regional averaging—is optimal. Whilst impulsive sampling *may* be most efficacious for high acuity tasks, functionally attaching a filter with spatial, or spatiotemporal, extent to each phosphene, and moreover a filter that can indicate orientation, motion, and location *within* its receptive field—that is, a kernel with shape—should improve scene cognition. We expect this improvement to be pronounced for scenes involving motion, such as in smooth pursuit, or when navigating an environment, as opposed to visual search of a “static” scene. This approach is depicted in Figure 4.

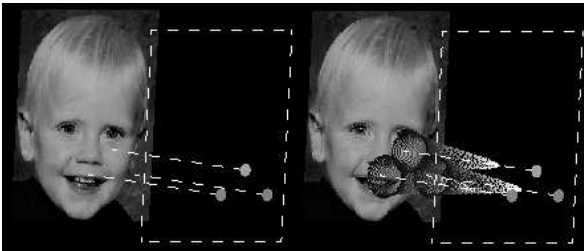


Figure 4—An approach involving spatial kernels for analyzing the stimulus. On the left is depicted the approach of Cha *et al.*: here, each phosphene’s intensity is that of its underlying pixel—that is, the underlying image is impulsively sampled at each phosphene location. On the right is depicted the authors’ proposed approach: the shaped spatial kernels better encode the underlying scene. For simplicity, in the image the filters depicted are circularly symmetric Gaussians, all of the same standard deviation; and three phosphenes are shown as opposed to, say, 100.

The vertebrate visual system exhibits two retinogeniculocortical pathways: M-cell and P-cell. The former comprises retinal ganglion cells (RGCs) with more expansive dendritic arbors, and therefore

more expansive receptive fields, which project to the visual cortex with greater temporal resolution. The latter exhibits RGCs with lesser arbors, and the delayed arrival of their signal at the cortex relative to M-cell pathways. Further, in humans, the ratio of P-cells to M-cells is higher in central areas of the retina and decreases with eccentricity (30). Studies have shown that some sufferers of Alzheimer’s disease (AD) have exhibited consistently good visual acuity despite visual decline in tasks that involve an image in motion on the retina, such as reaching for an object (31); it has been posited that adversely affected M-cell pathways in the visual systems are the cause of this (31). Now, the biological analogue of Cha’s pinholes is RGCs with extremely narrow dendritic arbors, and therefore narrow receptive fields, integral to high acuity tasks. The biological analogue of a strategy like we propose, depicted in the Figure, is RGCs with expansive arbors and receptive fields, better suited to “motion” tasks and peripheral visual tasks. In morphology studies, a ratio of 0.8 of dendritic expanse-to-RGC centre-to-centre has been found for cells at eccentricities 12 to 60 degrees (32). It follows that a strategy such as that depicted in the Figure should allow for better performance in “motion” tasks such as smooth pursuit (15).

The means by which the retinal neural image remains relatively unaliased in the periphery is debated, (33, 34, 35). Herein, Hirsch and Hylton note that eye movements mitigate aliasing:

“The assumption that the visual system has available only a single sampling of the image is questionable... eye motions generate successive independent spatial samples which could be used to resolve aliasing ambiguities when integrated over time.” (34)

A well known result in sampling theory states that, for optimal reconstruction, a signal for subsampling should first be low-pass filtered at the Nyquist frequency to avoid aliasing. This result indicates the above-mentioned approach of regional averaging. Such an approach, however, would make for marked loss in visual acuity. If eye movements serve to mitigate aliasing, then some strategy other than low-pass filtering at the Nyquist frequency should prove optimal.

The approach championed by Cha *et al.*, in assuming that “three parameters are important in determining the quality of a pixelized image: the number of pixels, their density, and their range of intensities” (19), clearly needs revisiting.

Further to the approach of Cha and derivatives, there exist the approaches of Boyle and co-workers, and of Eckmiller. The former does treat the issue of image processing as it applies to prosthetic vision (22). Here, numerous “intelligent” algorithms—algorithms that seek to identify important regions in the stimulus image, and ascribe “weight” to parameters such as depth and contrast, parameters which are elemental to the human visual system—are applied to scenes and presented to subjects via paper-based questionnaires. Said scenes—in the main, images of simple objects such as chairs—were rendered via regular, rectangular phosphene arrays of resolutions 10-by-10, 16-by-16, and 25-by-25 (23). Boyle’s approach is promising, and, when integrated with more linear approaches such as those suggested here, may form part of an elegant and important solution to the problem of prosthetic vision.

Eckmiller proposes a system comprising a Retina Encoder (RE) and a Retina Stimulator (RS) (24): the latter comprising between 100 and 1000 electrodes that deliver epiretinal stimuli; the former comprising the same number of tunable filters, delivered input by way of several thousand photosensors (presumably a head-mounted digital camera). The function of these filters is twofold: to respond selectively to visual stimulus; and, to provide a mapping from “pattern” space (PS) (that is, the visual stimulus) to ganglion-cell-activity space (GCAS) (that is, the action potentials propagated along the retinogeniculocortical tract by ganglion cells). It is proposed that 10 parameters (such as resting impulse rate, temporal components of the impulse delay) or fewer will allow the mapping to GCAS. Eckmiller’s RE is reported to currently implement some 200 tunable filters in quasi-real-time by way of adaptive neural networks. Regarding the filters’ responses to visual stimulus, Eckmiller proposes that user interface to the RE will, for each filter, allow the selection of “photosensors to the excitatory (+) or inhibitory (-) RF [receptive field] centre and another selectable set of adjacent photosensors for the RF periphery”.

As mentioned in previous paragraphs, existing approaches to epiretinal prosthesis employ large stimulating disk electrodes, of the order of several hundred micrometers in diameter. Accordingly, electrode array geometries small enough to selectively stimulate one or few RGCs may be decades in the realization. Given recent chronic trials in humans (10), early generations of retinal implants will precede a thorough understanding of charge injection at the vitreoretinal interface, the current paucity of which precludes the above-mentioned small electrode geometries. Indeed, for auditory neuroprosthesis, interfacing electrodes to spiral ganglion cells remains an active area of research (14).

RGCs respond selectively to specific spatiotemporal features in subregions, or receptive fields, of the visual field (for review, see Wassle & Boycott (36)). Since numerous RGCs survey any one point of the visual field, said spatiotemporal features can afford to be very selective, and thus the visual scene is encoded by many units and with “bearable” loss of information. If relatively few filters survey the visual field (as is the case with proposed epiretinal prostheses), however, they would need to respond more generally to spatiotemporal features so as to achieve more effective visual coding. In their paper, Eckmiller *et al.* (24) indicate that the receptive field properties of any RE filter mimic those of single RGCs: “outputs [act] as simulation of ganglion cell (G-cell) outputs generating impulse sequences for the stimulation of real G-cells.” For a disk electrode diameter of, say, 400 μm , charge injection would activate tens of thousands of RGCs. Accordingly, manipulation of underlying visual mechanisms is near impossible—by analogy, you can’t paint fine details with a broad brush, let alone paint those details simultaneously. Put differently, the aggregate receptive field of tens of thousands of RGCs would be effectively featureless.

Conclusion

The psychophysics of simulated prosthetic vision goes largely unaddressed in the burgeoning electronic vision prosthesis literature. In coming years, implantable neurostimulator design, and work at the neural interface in optimizing electrode design, will receive much focus; the parallel development of the psychophysics will inform said design and enhance clinical outcomes. The means of conveying prosthetic vision by way of relatively few phosphenes, a marked abbreviation of normal vision, is

largely conjectural at this stage. As a start, we argue that work should draw on filtering approaches derived from electrical engineering knowledge of image and signal processing.

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Figure 1

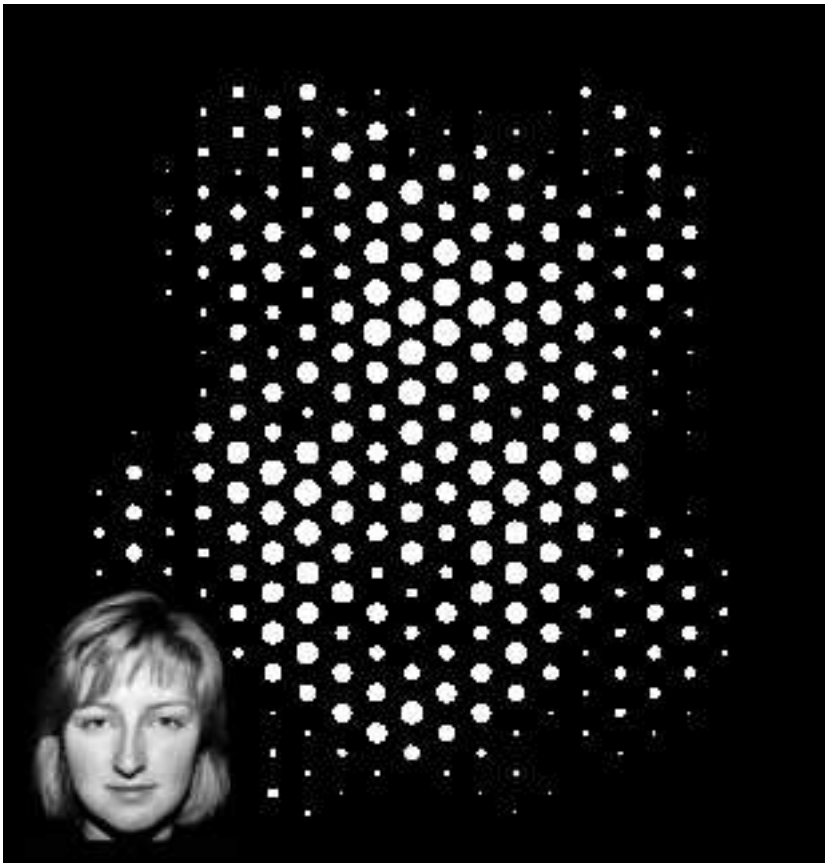


Figure 2

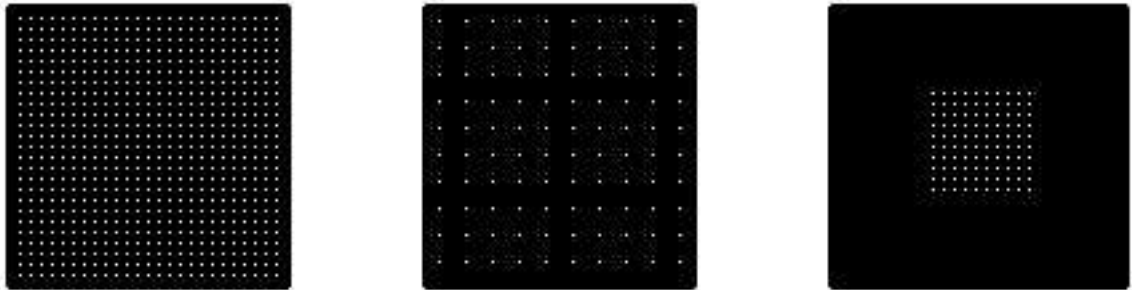


Figure 3

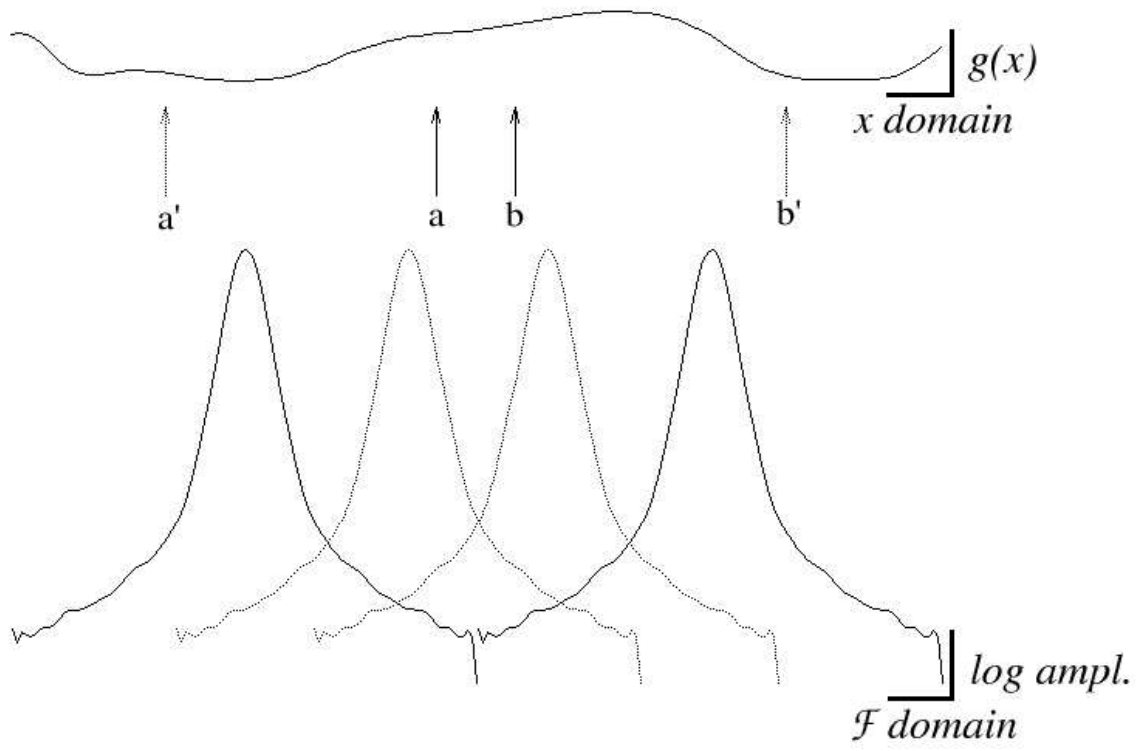


Figure 4

