

Perceptual evaluation of different image fusion schemes

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ABSTRACT

Human perceptual performance was tested with images of nighttime outdoor scenes. The scenes were registered both with a dual band (visual and near infrared) image intensified low-light CCD camera (DII) and with a thermal middle wavelength band (3-5 μm) infrared (IR) camera. Fused imagery was produced through a pyramid image merging scheme, in combination with different colour mappings. For all (individual and fused) image modalities, small patches of the scenes, displaying a range of different objects and materials, were briefly presented to human observers. The sensitivity of human observers was tested for different recognition tasks. The results show that greyscale image fusion yields improved performance levels for most perceptual tasks investigated here. When an appropriate colour mapping scheme is applied, the addition of colour to greyscale fused imagery significantly increases observer sensitivity for a given condition and a certain task. However, inappropriate use of colour significantly decreases observer performance compared to straightforward greyscale image fusion. This suggests that colour mapping should adapt to the visual task and the conditions (scene content) at hand.

Keywords: Image fusion, infrared, intensified visual, visual performance, detection, recognition, situational awareness

1. INTRODUCTION

Modern night-time camera's are designed to expand the conditions under which humans can operate. A functional piece of equipment must therefore provide an image that leads to good perceptual awareness in most environmental and operational conditions (to "Own the weather" or "Own the night"). The two most common nighttime imaging systems either display emitted infrared (IR) radiation or reflected light. IR cameras have a history of decades of development. Although modern IR cameras function very well under most circumstances, they still have some inherent limitations. For instance, after a period of extensive cooling (e.g. after a long period of rain or early in the morning) the infrared bands provide less detailed information due to low thermal contrast in the scene, whereas the visual bands may represent the background in great detail (vegetation or soil areas, texture). In this situation it can be hard or even impossible to distinguish the background of a target in the scene, using only the infrared bands, whereas the target itself may be highly detectable (when its temperature differs sufficiently from the mean temperature of its local background). A target that is well camouflaged for visual detection will be hard (or even impossible) to detect in the visual bands, whereas it can still be detectable in the thermal bands. A combination of visible and thermal imagery may then allow both the detection and the unambiguous localisation of the target (represented in the thermal image) with respect to its background (represented in the visual image). A human operator using a suitably combined or fused representation of IR and visual imagery may therefore be able to construct a more complete mental representation of the perceived scene, i.e. he will have a better situational awareness¹.

This study was performed to test the capability of several greylevel and colour image fusion schemes to combine and convey information, originating from different types of night vision systems, about both the *global structure* and the *fine detail* of scenes, to human observers. The image modalities used were dual band (visual and near infrared) intensified low-light CCD images (DII) and thermal middle wavelength band (3-5 μm) infrared images. Four different image fusion schemes were investigated. Colour and greyscale fused imagery was produced through a conventional pyramid image merging scheme, in combination with two different colour mappings. This fusion approach is representative for a number of methods that have been suggested in the literature²⁻⁷, and may serve as a starting point for further developments. Observer performance with the individual image modalities serves as a baseline for the performance that should be obtained with fused imagery. The results of these tests indicate to what extent DII and IR images are complementary, and can be used to identify the characteristic features of each image modality that determine human visual performance. The goal of image fusion is to combine and preserve in a single output image all the perceptually important signal information that is present in the individual input images. Hence, for a given observation task, performance with fused imagery should at least be as good (and preferably

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better) as performance with the individual image modality that yields the optimal performance for that task. Knowledge of the nature of the features in each of the input images that determine observer performance can be used to develop new multimodal image visualisation techniques, based on improved image fusion schemes that optimally exploit and combine the perceptually relevant information from each of the individual nighttime image modalities.

2. METHODS

2.1. Stimuli

A variety of outdoor scenes, displaying several kinds of vegetation (grass, heather, semi shrubs, trees), sky, water, sand, vehicles, roads, and persons, were registered at night with a dual-band visual intensified (DII) camera, with two bands covering the part of the electromagnetic spectrum ranging from visual to near infrared (400-900 nm), and with a thermal middle wavelength band (3-5 μm) infrared (IR) camera. The DII camera signal was stored as a colour image by mapping its two bands to the R and G channels respectively. The luminance component of the DII signal (II) was stored separately.

First, the images were registered through an affine warping procedure, using fiducial registration points that were recorded at the beginning of each session. After warping, corresponding pixels in images taken with different cameras represent the same location in the recorded scene. Then, patches displaying different types of scenic elements were selected and cut out from corresponding images (i.e. images representing the same scene at the same instant in time, but taken with different cameras). These patches were deployed as stimuli in the psychophysical tests. The signature of the target items (i.e. buildings, persons, vehicles etc.) in the image test sets varied from highly distinct to hardly visible.

To test the *perception of detail*, patches were selected that display either buildings, vehicles, water, roads, or humans. These patches are 280×280 pixels², corresponding to a 1.95×1.95 deg² camera field of view.

To investigate the *perception of global scene structure*, larger patches were selected, that represent either the horizon (to perform a horizon perception task), or a large amount of different terrain features (to enable the distinction between an image that is presented upright and one that is shown upside down). These patches are 575×475 pixels², corresponding to a 4×3.3 deg² camera field of view.

To test if the combined display of information from the individual image modalities may enhance the perception of detail (target recognition) and situational awareness, corresponding stimulus pairs (i.e. patches representing the same part of a scene at the same instant in time, but taken with different cameras) were fused.

Greyscale fused images were produced using a pyramidal image fusion scheme²⁻⁴. A 7-level Laplacian pyramid² was used, in combination with a maximum absolute contrast node (i.e. pattern element) selection rule. The following two combination methods were applied.

Greyscale Fusion Method 1 (GF1): The IR and II images were taken as the two input modalities.

Greyscale Fusion Method 2 (GF2): The IR and the luminance component of the DII images were adopted as the two input modalities.

Colour fused imagery was produced by the following two methods.

Colour Fusion Method 1 (CF1): The short and long wavelength bands of the DII camera were respectively mapped to the R and G channels of an RGB colour image. The resulting RGB colour image was then converted to the YIQ (NTSC) colour space. The luminance (Y) component was replaced by the corresponding aforementioned greyscale (II and IR) fused image, and the result was transformed back to the RGB colour space. This colour fusion method results in images in which grass, trees and persons are displayed as greenish, and roads, buildings, and vehicles are brownish.

Colour Fusion Method 2 (CF2): First, an RGB colour image was produced by assigning the IR image to the R channel, the long wavelength band of the DII image to the green channel (as in Method 1), and the short wavelength band of the DII image to the blue channel (instead of the red channel, as in Method 1). This colour fusion method results in images in which vegetation is displayed as greenish, persons are reddish, buildings are red-brownish, vehicles are whitish/bluish, and the sky and roads are most often bluish.

The multiresolution greyscale image fusion scheme employed here, selects the perceptually most salient contrast details from both of the individual input image modalities, and fluently combines these pattern elements into a resulting (fused) image. As a side effect of this method, details in the resulting fused images can be displayed at higher contrast than they appear in the images from which they originate, i.e. their contrast may be enhanced^{8,9}. To distinguish the perceptual effects from contrast enhancement from those of the fusion process, observer performance was also tested with contrast enhanced versions of the individual image modalities. The contrast in these images was enhanced by a multiresolution local contrast enhancement scheme. This scheme enhances the contrast of perceptually relevant details for a range of spatial scales, in a way that is similar to the approach used in the hierarchical fusion scheme. A detailed description of this enhancement method is given elsewhere^{8,9}.

2.2. Apparatus

A Pentium II 400 MHz computer is used to present the stimuli, measure the response times and collect the observer responses. The stimuli are presented on a 17 inch Vision Master 400 (Iiyama Electric Co., Ltd) colour monitor, using the 1152×864 true colour (32 bit) mode (corresponding to a resolution of 36.2 pixels/cm), with a colour temperature of 6500 K, and a 100 Hz refresh rate.

2.3. Tasks

The perception of the *global structure* of a depicted scene was tested in two different ways. In the first test, scenes were presented that had been randomly mirrored along the horizontal, and the subjects were asked to distinguish the orientation of the displayed scenes (i.e. whether a scene was displayed right side up or upside down). In this test, each scene was presented twice: once upright and once upside down. In the second test, horizon views were presented together with short markers (55×4 pixels) on the left and right side of the image and on a virtual horizontal line. In this test, each scene was presented twice: once with the markers located at the true position (height) of the horizon, and once when the markers coincided with a horizontal structure that was opportunistically available (like a band of clouds) and that may be mistaken for the horizon. The task of the subjects was to judge whether the markers indicated the true position of the horizon. The perception of the global structure of a scene probably determines situational awareness.

The capability to discriminate *fine detail* was tested by asking the subjects to judge whether or not a presented scene contained an exemplar of a particular category of objects. The following categories were investigated: buildings, vehicles, water, roads, and humans. The perception of detail is relevant for tasks involving visual search, detection and recognition. The tests were blocked with respect to both (1) the imaging modality and (2) the task. This was done to minimise observer uncertainty, both with respect to the characteristics of the different image modalities, and with respect to the type of target.

Blocking by image modality yielded the following seven classes of stimuli:

1. Greyscale images representing the thermal 3-5 μm IR camera signal.
2. Greyscale images representing the luminance component (II) of the DII images.
3. Colour (R and G) images representing the two channels of the DII.
4. Greyscale images representing the IR and II signals fused by GF1.
5. Greyscale images representing the IR and II signals fused by GF1.
6. Colour images representing the IR and DII signals fused by CF1.
7. Colour images representing the IR and DII signals fused by CF2.

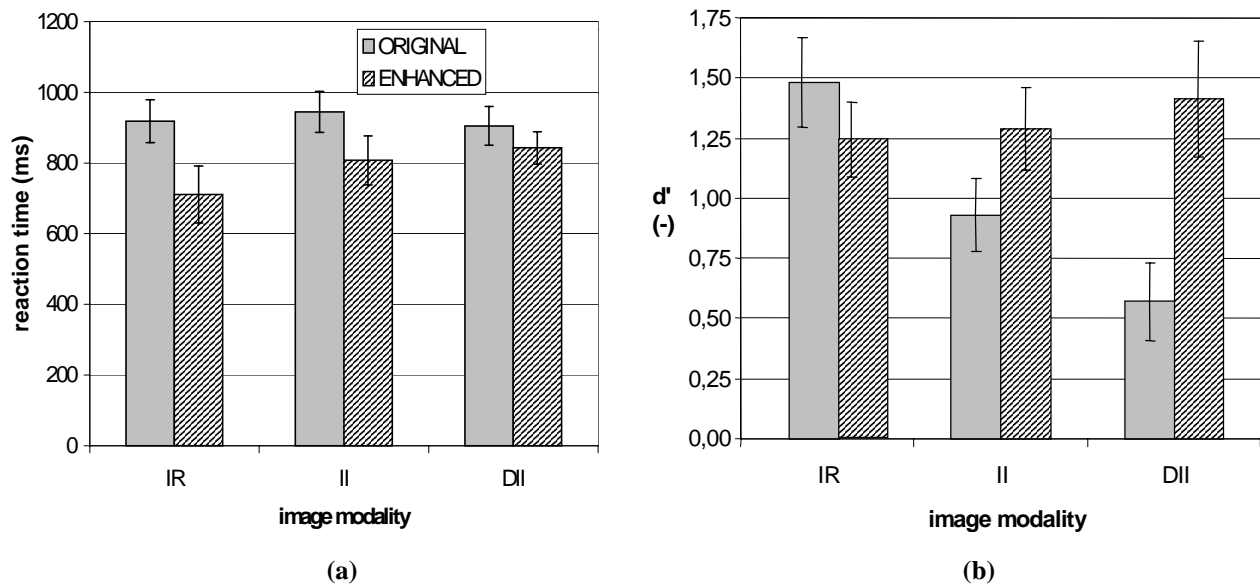


Figure 1 : The effect of contrast enhancement on mean reaction time (a) and sensitivity d' (b).

Blocking by task resulted in trial runs that tested the perception of global scene structure by asking the observers to judge whether

- the horizon was veridically indicated
- the image was presented right side up

and the recognition of detail by asking the observers to judge whether the image contained an exemplar of one of the following categories:

- building
- person
- road or path
- fluid water (e.g. a ditch, a lake, a pond, or a puddle)
- vehicle (e.g. a truck, car or van)

The entire experiment consisted of 42 different trial runs (6 different image modalities \times 7 different tasks). The order in which the image modalities and the tasks were tested was randomly distributed over the observers.

2.4. Procedure

Before starting the actual experiment, the observers were shown examples of the different image modalities that were tested. They received verbal information, describing the characteristics of the particular image modality. It was explained how different types of targets are displayed in the different image modalities. This was done to familiarise the observers with the appearance of the scene content in the different images modalities, thereby minimising their uncertainty.

Next, subjects were instructed that they were going to watch a sequence of briefly flashed images, and that they had to judge each image with respect to the task at hand. For a block of trials, testing the perception of detail, the task was to judge whether or not the image showed an exemplar of a particular category of targets (e.g. a building). For a block of trials, testing the perception of the overall structure of the scene, the task was to judge whether the scene was presented right side up, or whether the position of the horizon was indicated correctly. The subjects were instructed to respond as quickly as possible after the onset of a stimulus presentation, by pressing the appropriate one of two response keys.

Each stimulus was presented for 400 ms. This brief presentation duration, in combination with the small stimulus size, served to prevent scanning eye movements (which may differ among image modalities and target types), and to force subjects to make a decision based solely on the instantaneous percept aroused by the stimulus presentation. Immediately after the stimulus presentation interval, a random noise image was shown.. This noise image remained visible for at least 500 ms, and

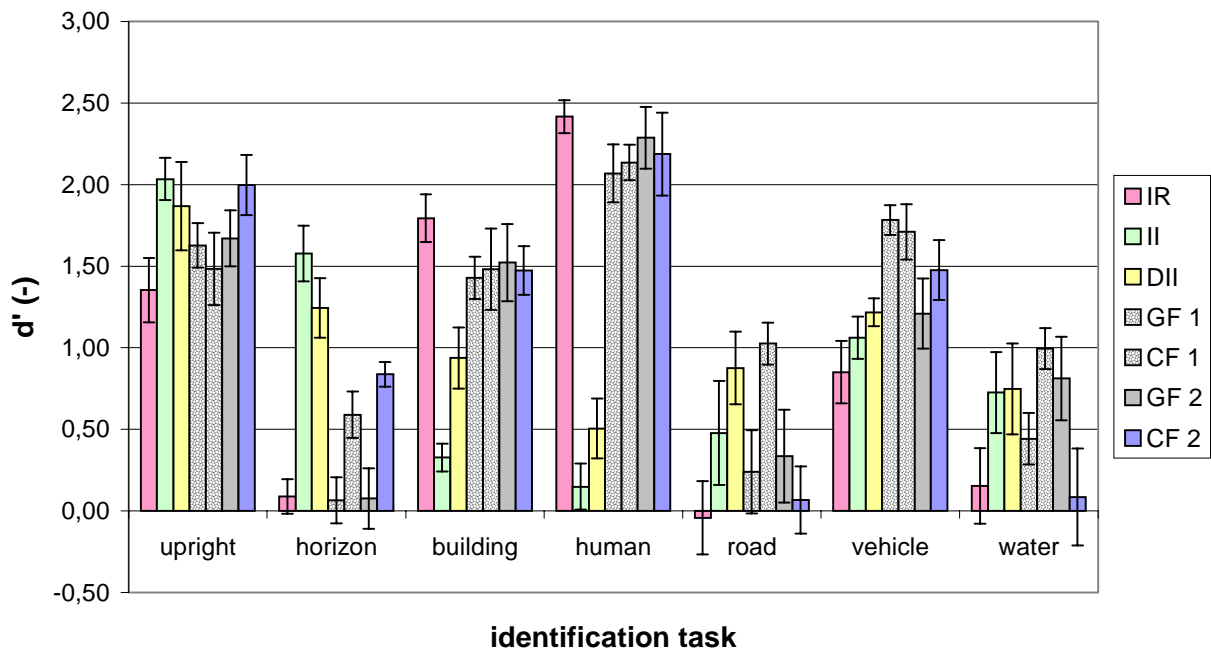


Figure 2. Observer sensitivity d' for discrimination of global layout (orientation and horizon) and local detail (buildings, humans, roads, vehicles, and water), for seven different image modalities. These modalities are (in the order in which they appear in the labeled clusters above): infrared (IR), greyscale (II) and colour (DII) intensified visual, and two different greyscale (GF1, GF2) and colour fusion (CF1, CF2) schemes.

served to erase any possible afterimages (reversed contrast images induced by, and lingering on after, the presentation of the stimulus, that may differ in quality for different image modalities and target types), thereby equating the processing time subjects can use to make their judgement. Upon each presentation, the random noise image was randomly left/right and up/down reversed. The noise images had the same dimensions as the preceding stimulus image, and consisted of randomly distributed sub-blocks of 5×5 pixels. For trial blocks testing the monochrome IR and II imaging modalities and greyscale fused imagery, the noise image sub-blocks were either black or mean grey. For trial blocks testing DII and colour fused imagery, the noise image sub-blocks were randomly coloured, using a color palette similar to that of the modality being tested. In all tests, subjects were asked to quickly indicate their visual judgement by pressing one of two response keys (corresponding to a YES/NO response), immediately after the onset of a stimulus image presentation. Both the accuracy and the reaction time were registered.

2.5. Subjects

A total of 12 subjects, aged between 20 and 55 years, served in the experiments reported below. All subjects have corrected to normal vision, and no known colour deficiencies.

2.6. Viewing conditions

The experiments were performed in a dimly lit room. The images are projected onto the screen of the CRT display. Viewing was binocular, at a distance of 60 cm. At this distance, the images subtended a viewing angle of either 14.8×12.3 or 7.3×7.3 degrees², corresponding to a scene magnification of 3.8.

3. RESULTS

This section reports the results of the observer experiments for the different tasks and for each of the aforementioned image modalities. The first two tasks measure the degree to which the scene structure is correctly perceived. The remaining 5 tasks measure the perception of detail.

For each visual discrimination task the numbers of hits (correct detections) and false alarms (fa) were recorded to calculate $d' = Z_{\text{hits}} - Z_{\text{fa}}$, an unbiased estimate of sensitivity¹⁰.

The effects of *contrast enhancement* on human visual performance is found to be similar for all tasks. Figure 1a shows that contrast enhancement results in a decrease in the overall (i.e. the mean over all tasks) reaction time for each of the imaging modalities. Figure 1b shows that contrast enhancement significantly improves the sensitivity of human observers performing with II and DII imagery. However, for IR imagery, the sensitivity decreases as a result of contrast enhancement. This is probably a result of the fact that contrast enhancement increases the visibility of irrelevant detail and clutter in the scene.

Figure 2 shows the results of all scene recognition and target detection tasks investigated here. As stated before, the ultimate goal of image fusion is to produce a combined image that displays more information than either of the original images. Figure 2 shows that this aim is only achieved for the following perceptual tasks and conditions:

- the detection of roads, where CF1 outperforms each of the input image modalities,
- the recognition of water, where CF1 yields the highest observer sensitivity, and
- the detection of vehicles, where three fusion methods tested perform significantly better than the original imagery.

These tasks are also the only ones in which CF1 performs better than CF2. An image fusion method that always performs at least as good as the best of the individual image modalities can be of great ergonomic value, since the observer can perform using only a single image. This result is obtained for the recognition of scene orientation from colour fused imagery produced with CF2, where performance is similar to that with II and DII imagery. For the detection of buildings and humans in a scene, all three fusion methods perform equally well and slightly less than IR. CF1 significantly outperforms greyscale fusion for the detection of the horizon and the recognition of roads and water. CF2 outperforms greyscale fusion for both global scene recognition tasks (orientation and horizon detection). However, for CF2 observer sensitivity approaches zero for the recognition of roads and water.

Rather surprisingly, the response times (not shown here) did not differ significantly between image modalities. The shortest reaction times were obtained for the detection of humans (about 650 ms), and the longest response times were found for the detection of the position of the horizon (about 1000 ms).

The following section discusses the results in detail for each of the seven different perception tasks.

3.1. Perception of global structure

The perception of the *scene layout* was tested by measuring the accuracy with which observers could distinguish a scene that was presented right side up from one that was presented upside down, and perceive the position of the horizon.

The first group of bars in Figure 2 (labelled "upright") represents the results for the *scene orientation* perception task. For the original image modalities, the best results are obtained with the intensified imagery (the II performed slightly better than the DII). The IR imagery performs significantly worse. CF2 performs just as well as II, whereas CF1 performs similar to IR. Greylevel fusion is in between both colour fusion methods. Observers remarked that they based their judgement mainly on the perceived orientation of trees and branches in the scene. CF2 displays trees with a larger colour contrast (red-brown on a light greenish or bluish background) than CF1 (dark green trees on a somewhat lighter green background), resulting in a better orientation detection performance. Also, CF2 produces bright blue skies most of the time, which makes the task more intuitive. This result demonstrates that the application of an appropriate colour mapping scheme in the image fusion process can indeed significantly improve observer performance compared to greyscale fusion. In contrast, the use of an inappropriate colour scheme can severely degrade observer sensitivity.

The perception of the true *position of the horizon*, represented by the second group of bars in Figure 2, is best performed with II imagery, followed by the DII modality. Both intensified visual image modalities perform significantly better than IR or any kind of fused imagery. The low performance with the IR imagery is probably a result of the fact that a tree line and a band of clouds frequently have a similar appearance in this modality. The transposition of these ‘false horizons’ into the fused image modalities significantly reduces observer performance. For greylevel fused imagery, the observer sensitivity is even reduced to a near-zero level, just as found for IR. Colour fused imagery restores some of the information required to perform the task, especially CF2 that produces blue skies. However, the edges of the cloud bands are so strongly represented in the fused imagery that observer performance never attains the sensitivity level obtained for the intensified visual modalities alone (II and DII).

In both the orientation and horizon perception tasks subjects tend to confuse large bright areas (e.g. snow on the ground) with the sky.

3.2. Perception of detail

The best score for the recognition of *buildings* is found for IR imagery. In this task, IR performs significantly better than II or DII. DII imagery performs significantly better than II, probably because of the colour contrast between the buildings and the surrounding vegetation (red-brown walls on a green background, compared to grey walls on a grey background in case of the II imagery). The performance with fused imagery is slightly less than with IR, and independent of the fusion method.

The detection of *humans* is best performed with IR imagery, in which they are represented as white hot objects on a dark background. II imagery yields a very low sensitivity for this task; i.e. humans are hardly ever noticed in intensified visual imagery. The sensitivity for the detection of humans in DII imagery is somewhat higher, but remains far below that found for IR. In this case, there is almost no additional information in the second wavelength band of the DII modality, and therefore almost no additional colour contrast. As a result, most types of clothing are displayed as greenish, and are therefore hard to distinguish from vegetation. Performance with fused imagery is only slightly below that with IR. There is no significant difference between the different greyscale and colour fusion types.

Roads cannot reliably be recognized from IR imagery (d' becomes even negative, meaning that more false alarms than correct detections are scored). DII performs best of the individual image modalities, and significantly higher than II because of the additional colour contrast (DII displays roads as red-brown, on a green background). Greyscale fused imagery results in a performance that is significantly below that found for DII, and somewhat lower than that obtained for II imagery. This is probably a result of (1) the introduction of irrelevant luminance details from the IR imagery, and (2) the loss of colour contrast as seen in the DII imagery. CF1 produces colour fused imagery that yields a higher sensitivity than each of the original image modalities, although observer performance is not significantly better than with DII imagery. The additional improvement obtained with this combination scheme is probably caused by the contrast enhancement inherent in the fusion process. The sensitivity obtained for imagery produced by CF2 is near zero. This is probably a result of the fact that this method displays roads with a light blue colour. These can therefore easily be mistaken for water or snow. This result demonstrates that the inappropriate use of colour in image fusion severely degrades observer performance.

Image fusion clearly helps to recognize *vehicles* in a scene. They are best discriminated in colour fused images produced with CF1, that displays vehicles in brown-yellow on a green background. CF2 (that shows vehicles as blue on a brown and green background) and greyscale fusion both result in an equal and somewhat lower observer sensitivity. Fused imagery of all types performs significantly better than each of the original image modalities. The lowest recognition performance is obtained with IR imagery.

Water is best recognised in colour fused imagery produced with CF1. This method displays water sometimes as brown-reddish, and sometimes as greyish. The II, DII and greylevel fusion scheme all yield a similar and slightly lower performance. CF2 results on a near zero observer sensitivity for this task. This method displays water sometimes as purple-reddish, thus giving it a very unnatural appearance, and sometimes as bluish, which may cause confusion with roads, that have the same colour. These results again demonstrate that it is preferable not to use any colour at all (greyscale), than to use an inappropriate colour mapping scheme.

3.3. Summary

Table I summarizes the main findings of this study. IR has the lowest overall performance of all modalities tested. This results from a low performance for both large scale orientation tasks, and for the detection and recognition of roads, water, and vehicles. In contrast, intensified visual imagery performs best in both orientation tasks. The perception of the horizon is significantly better with II and DII imagery. IR imagery performs best for the perception and recognition of buildings and humans. Fused imagery yields slightly less sensitivity for these tasks. II and DII perform complementary to IR. DII has the best overall performance of the individual image modalities. CF1 has the best overall performance of the image fusion schemes tested here.

4. CONCLUSIONS

Since there obviously exists no one-to-one mapping between the temperature contrast and the spectral reflectance of a material, the goal of producing a nighttime image with an appearance similar to a colour daytime image can never be fully achieved. The options are therefore (1) to settle for a single mapping that works satisfactory in a large number of conditions, or (2) to adapt (optimize) the colour mapping to the situation at hand. However, the last option is not very attractive since a different colour mapping for each task and situation tends to confuse observers^{11,12}.

Multimodal image fusion schemes based on local contrast decomposition do not distinguish between material edges and temperature edges. For many tasks, material edges are the most important ones. Fused images frequently contain an abundance of contours that are irrelevant for the task that is to be performed. Fusion schemes incorporating some kind of contrast stretching enhance the visibility of all details in the scene, irrespective of their visual significance. The introduction of spurious or irrelevant contrast elements in a fused image may clutter the scene, distract the observer and lead to misinterpretation of perceived detail. As a result, observer performance may degrade significantly. A useful image fusion scheme should therefore take into account the visual information content (meaning) of the edges in each of the individual image modalities, and combine them accordingly in the resulting image.

For most perceptual tasks investigated here (except for horizon and road detection), greyscale image fusion yields appreciable performance levels. When an appropriate colour mapping scheme is applied, the addition of colour to greyscale fused imagery can significantly increase observer sensitivity for a given condition and a certain task (e.g. Colour Fusion Method 2 for orientation detection, both colour fusion methods for horizon detection, Colour Fusion Method 1 for road and water detection). However, inappropriate use of colour can significantly decrease observer performance compared to straightforward greyscale image fusion (e.g. Colour Fusion Method 2 for the detection of roads and water).

The present findings agree with those from previous studies¹¹⁻¹⁴. The present results will be analysed further

1. to distinguish perceptually relevant features from noise and distracting elements, and
2. to find out if there are features that are consistently mistaken by subjects for another type of scenic detail.

Summarizing, the main findings of this study are that in image fusion:

- Contrast stretching should only be applied if the visual significance of the enhanced details is taken into account,
- Colour mapping should adapt to the visual task and the conditions (scene content) at hand.

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