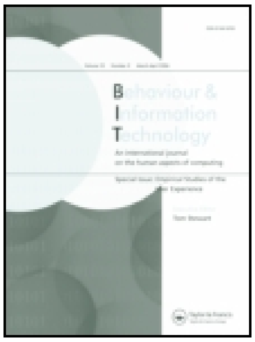

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Colour size illusion on liquid crystal displays and design guidelines for bioinformatics tools

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Although the influence of colour on size perception has been known for a century, there is only limited research on interventions that can reduce this effect. This study was therefore undertaken in order to identify appropriate interventions and propose design guidelines for information visualisation, especially in applications where size judgement is critical. The colour size illusion was replicated on an LCD monitor, revealing that yellow images appeared the smallest among a series of red, yellow, green and blue images on a white background. Three types of interventions (background brightness, border colour and background grid brightness) were tested to identify conditions that reduce the colour illusions, but none proved to be statistically significant. Based on these experimental results and an extensive literature survey, a set of design guidelines is proposed to enhance the usability of LCD monitors and a set of design recommendations given to extend these guidelines to applications in the field of bioinformatics. These design recommendations are accompanied by an evaluation of effectiveness obtained by interviewing domain experts.

Keywords: colour; size; illusion; liquid crystal display; design guidelines; bioinformatics

1. Introduction

Colour is widely used in information visualisation to deliver different types of information such as extreme values, patterns and attribute values. Colour coding is known to be a particularly effective way to represent extreme values for human viewers because of the nature of pre-attentive vision (Julész 1981). Researchers have demonstrated that colour takes priority over other visual properties for nominal data mapping (Christ 1975, Cleveland and McGill 1984, Mackinlay 1986, Nowell *et al.* 2002). In the case of quantitative data, there is some evidence that colour conveys quantitative data more accurately than either shape or size (Christ 1975, Nowell *et al.* 2002). These findings are partially supported by Cleveland and McGill (1984) and Mackinlay (1986), who found that although colour is more accurate than shape, it is less accurate than either size or volume. Additionally, many display design guidelines suggest redundant colour coding, since it enhances visual search performance (Christ 1975, Cahill and Carter 1976, Carter 1982, Bundesen and Pedersen 1983, Treisman and Gormican 1988, Hughes and Creed 1994).

Nevertheless, colour should be carefully used because of the inherent characteristics of human visual perception. Cleveland and McGill (1983) reported that participants in their study often erred in judging the size of coloured areas in statistical maps, Claessen *et al.* (1995) reported that subjects consistently selected larger or smaller pegs to fit a hole when the peg was coloured. These empirical studies imply that colour has an influence on size perception and can result in human errors.

The influence of colour on size perception has been known for a long time, with a series of research studies showing that the colour of an object influences its perceived size (Gundlach and Macoubrey 1931, Wallis 1935, Cleveland and McGill 1983, Tedford *et al.* 1977, Gentilucci *et al.* 2001). The researchers in these studies used a variety of media, including slide projectors, coloured boards, coloured cubes and cathode ray tube (CRT) monitors, to replicate the colour size illusion, but this study is the first to utilise liquid crystal display (LCD) monitors.

We chose LCD monitors as a medium of the colour size illusion because these are rapidly replacing CRT monitors in our workplaces and homes. LCD monitors use less space and energy than CRT monitors, and their cost has declined to the point where they are now very affordable. It has also been shown that visual display terminal (VDT) workers prefer TFT-LCD to CRT monitors (Chen and Lin 2004). Accordingly, it is likely that their use will continue to increase. Therefore, in order to provide a useful foundation for

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further research, it would be meaningful to confirm whether or not the colour size illusion also occurs on LCD monitors.

2. Background

2.1. *The influence of colour on size perception*

It has long been known that three components of colour affect size perception. Brightness was the first component that was identified as having an influence on size perception (Payne 1964). Tedford *et al.* (1977) conducted research controlling hue, brightness and saturation and found that both hue and saturation have an effect. These findings are consistent with previous research (Gundlach and Macoubrey 1931, Wallis 1935). Recently, a kinematic study also confirmed the influence of colour on size perception (Gentilucci *et al.* 2001).

2.2. *Empirical evidence for the colour size illusion*

Cleveland and McGill (1983) provided considerable empirical evidence for the colour size illusion with the aid of a statistical map that displayed the state of Nevada with some of the counties coloured red and others green. Almost half of the participants considered the red counties to be bigger, whereas only 22% of the participants judged the green areas to be bigger. They concluded that those constructing statistical graphs should be careful in their use of colour, since it may affect viewers' perceptions of the data on the graphs. This conclusion implies that unfortunate colour choices could be a source of human error in some applications, for example, in a bioinformatics visualisation, such as a genome browsing application, where the interface was designed to enable viewers to process data based on the size of coloured objects.

Another empirical study used puzzle pegs (Claessen *et al.* 1995), where participants were given different sized pegs and asked to select the peg they thought would be best fit a hole. The experiments were varied by using two different types of puzzles (real puzzles and computer simulations), two different colours (red and blue) and two different brightness levels (light and dark). The researchers found the same pattern with self-luminous colours shown on a computer screen (CRT), thus confirming the hypotheses on the effect of hue and brightness. This study revealed that the colour size illusion significantly influenced the user's task and was therefore potentially a direct cause of human error.

2.3. *Complexity in the human vision system*

Colour perception is a result of human vision interaction. Human colour vision is not a simple reaction of colour receptors; rather it is a complex system composed of sensors (the trichromatic theory) (Wald 1968), a gain control system (the opponent-process theory of colour vision) (Hering 1920, DeValois 1965, Bornstein *et al.* 1976, Michael 1978, Gordon *et al.* 1994) and an error recovery system (the retinex theory) (Land and McCann 1971, Land *et al.* 1983).

Simultaneous brightness contrast and brightness assimilation (Shapley and Reid 1985) are good examples of colour interaction. Simultaneous brightness contrast describes a phenomenon in which background brightness affects the viewer's perception of the brightness of a central image superimposed on that background. This phenomenon is explained by the lateral inhibition theory (Hartline and Ratliff 1957, Arend 1993). A dark background inhibits the brightness reception of the central object, making it seem brighter than it actually is.

Brightness assimilation is an opposite case. Brightness assimilation describes a phenomenon in which background brightness affects the viewer's perception of brightness, making it appear similar to the background brightness. Similar phenomena affect how colours are seen, where they are referred to as simultaneous colour contrast and colour assimilation, respectively.

Efforts to understand colour interaction have been expanded to suggest a mathematical model describing the influence of adjacency on colour interaction (Kjelldall and Schenkman 2007).

2.4. *Interventions to reduce the colour size illusion*

Given that brightness is a component of colour that influences size perception (Payne 1964), it is possible that the colour size illusion can be reduced by altering the brightness of an object. As explained above, according to research on simultaneous brightness contrast and brightness assimilation, background brightness can change the perceived brightness of a centred object that is either similar to or different from the background brightness (Shapley and Reid 1985). Consequently, five different levels of background brightness were used in the current study to test the effectiveness of utilising background brightness as a potential intervention to reduce the colour size illusion.

In addition to background brightness, it seems possible that additional visual cues such as borders or background grids help people judge size more accurately. The addition of a border may help distinguish a target object from its background and allow viewers to see both ends more clearly. However, in adding a border around the central object, many design factors must be considered, including its width, colour (hue, brightness, saturation) and style (solid line, dashed line) among others. Since there have been no previous reports concerning the influence of border design factors on the colour size illusion, this study considered relatively simple factors: three brightness levels and one saturation level. The border width was fixed at two pixels, based upon a study that argued a two-pixel border was wide enough to distinguish an icon on an LCD monitor (Huang and Chiu 2007).

Incorporating a background grid opens up yet more design options, including the colour of the background grid (hue, brightness, saturation), grid line style (solid, dashed), grid pattern (vertical line, horizontal line, or both), grid line width, grid frequency and so on. Once again lacking any guidance from prior studies, this study started by examining the effect of the simplest factor, background grid brightness, by testing five levels of background grid brightness as an intervention.

The first objective of this study was to replicate the colour size illusion on an LCD monitor (experiment 1). The second objective was to identify interventions that would minimise these colour illusions, which would, in turn, enable the construction of design guidelines. Background brightness (experiment 2), border colour (experiment 3) and grid brightness (experiment 4) were evaluated as possible interventions.

This study tested three interventions expected to reduce the influence of colour and enhance decision-making performance. Based on the results, a set of design guidelines is proposed for use in situations where the visual perception of size is critical.

3. Method

3.1. Participants

Twenty-four university students (14 men, 10 women), between 19 and 36 years of age ($M = 26.9$, SD = 5.92), participated in the study. An acuity screening inventory (Coren and Hakstian 1989) was used to measure visual acuity. Participants either had normal vision or corrected to 20/20 Snellen or better Snellen with the exception of one participant whose Snellen score was 20/40 (near normal vision). Every participant passed 10 Ishihara colour plate tests with 100% accuracy.

3.2. Rationale

In this study, participants were asked to compare a pair of identically sized but differently coloured bars to assess their apparent size (Gundlach and Macoubrey 1931, Tedford *et al.* 1977, Cleveland and McGill 1983). If the LCD monitor had no effect on the mechanism of the colour size illusion, then the results would agree with those reported in the CRT monitor study conducted by Claessen *et al.* (1995). Once this had been established, it was expected that the colour size illusion would not be observed, or would be observed to a lesser extent, if adjusting the level of background brightness reduced the influence of colour on apparent size. Further tests involving changing the border colour saturation and brightness used for the comparison object and the background grid brightness were utilised.

3.3. Experimental design

The design of experiment 1 was a 6 (hue pairs) $\times$ 2 (saturations) full factorial within-subjects design. Hue pairs were red-yellow, red-green, red-blue, yellow-green, yellow-blue and green-blue. Saturations were varied by 100% and 75%. Each hue pair/saturation level set was measured twice by reversing their relative position; thus position was used to control for potential order effects. For example, in a red-yellow comparison, red was displayed on the upper side once (straight) and lower side once (inverted). The Commission Internationale de l'Eclairage (CIE) values used in this experiment are listed in Table 1. The stimulus was a rectangular bar, 50 pixels in width (1.15 cm) and 10 pixels in height (0.23 cm), and the lower bar was located 30 pixels down apart (0.7 cm). Since the measured size can be varying depends on the monitors, one monitor was used throughout the experiments. White was used for all the backgrounds as a control.

The design of experiment 2 was a within-subjects design employing five background brightness levels. Background brightness levels of 0% (black), 25% (dark gray), 50% (gray), 75% (light gray) and 100% (white) were used. The red-green hue pair used in experiment 1 was also used for experiments 2 through 4, since this pair was the extreme case in the previous research (Tedford *et al.* 1977). Similar to experiment 1, position was used to control for order effects.

Experiment 3 was a within-subjects design using four border colours. Border colours consisted of pure black (brightness 0%), gray (brightness 50%), less saturation of the colour of object and no border. The width of the border was set to 2 pixels (Huang and

Table 1. Chromaticity coordinates (CIE L*a*b) of colours used in experiments.

Hue	Saturation	CIE L	CIE a	CIE b
Red	High	56.925	79.465	79.215
Yellow	High	96.863	−13.754	96.922
Green	High	85.634	−83.219	81.219
Blue	High	33.783	53.875	−105.785
Red	Low	62.586	66.180	44.219
Yellow	Low	97.130	−12.520	80.016
Green	Low	86.987	−72.637	64.918
Blue	Low	46.384	35.207	−84.828
White	N/A	100	0	0

Chiu 2007), and white was again used for the background as a control.

Experiment 4 utilised five levels of background grid brightness in a within-subjects design. The brightness of background grid was varied by five levels; black (0%), 25%, 50%, 75% and white (no grid, equivalent to a white background). The width of grid was set to 2 pixels (Huang and Chiu 2007) and frequency of grid lines was set to 20 pixels. White, in this case corresponding to the no grid case, was used for the background as a control.

3.4. *Dependent variables*

The difference in the apparent size was measured in experiments 1–4. Participants were asked in each trial, 'Which bar is longer than the other?' and answered by selecting one of the following choices: 'No difference', 'Upper bar is longer' or 'Lower bar is longer'.

In addition to the perceived size, this study also examined the effect of colour on decision-making performance by posing a seven point Likert-type scale question, 'Rate the difficulty of making your decision'. These subjective ratings were supplemented by measuring the response time as an objective measure of decision-making performance.

3.5. *Equipment and apparatus*

The experiment was conducted in a room in which the interior walls were painted gray in order to minimise glare. The room had a normal ambient illumination as well. Two black display boards were placed around the display and participant for two purposes; to limit the effect of visual stimuli on peripheral vision, and to minimise the glare on the screen. A chin-mount was used to fix the distance between participants and the display at 57.5 cm. Luminance measured on the display was 220 cd/m^2 on average (deviation within $\pm$5 cd/m^2). An Apple Cinema Display^{TM} and a Power Mac G5^{TM} were used to run the experiment. A monitor calibration system (Spyder2PRO^{TM}) was used to set the correct colour profile and a luminance meter (Minolta nt-1°) measured the luminance on the LCD screen. To obtain the chromaticity coordinates (Table 1), a DigitalColor Meter^{TM} was used.

4. Results

4.1. *Colour size illusion on LCD monitors*

The existence of the colour size illusion on LCD monitors was confirmed by observing size judgement errors using a chi-square tests due to the use of binary values/nominal. Depending on the comparison pairs (hue and saturation levels), size judgement errors ranging from 17% to 52% were observed (Figure 1). As the bars were identical in length, answers in which either of the hue pairs was considered to be longer than the other were counted as an error. When the red and yellow were compared, over 50% of responses were errors in both high and low saturation. In the case of highly saturated colours, 24 errors were made that

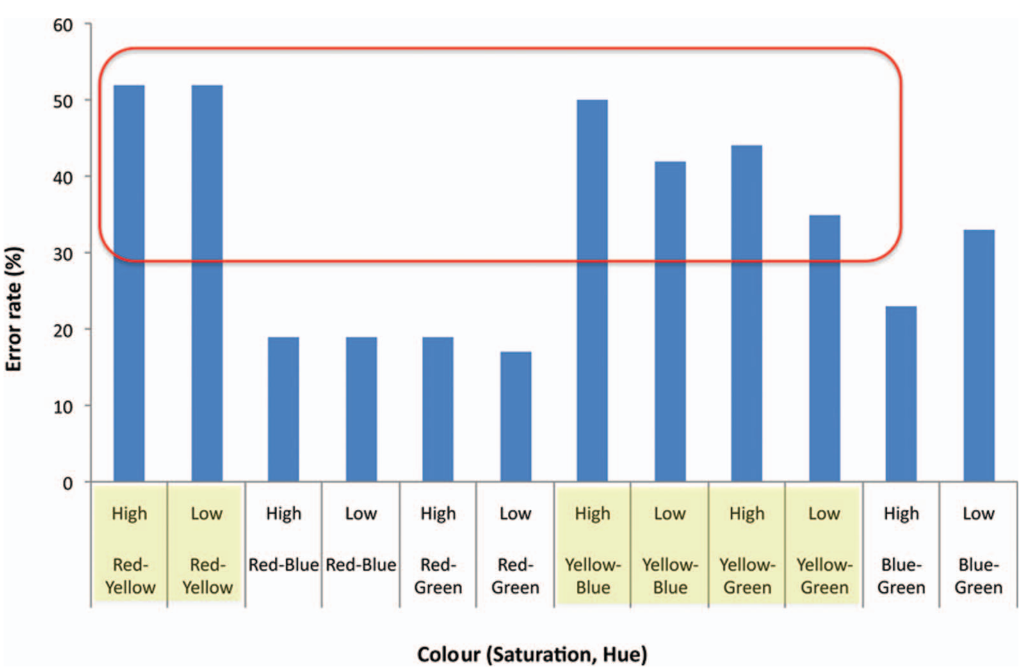

Figure 1. Error rates in size judgement.

indicated the red bar was longer, one selected yellow as longer and 23 responses were correct and indicated that the two bars were the same. In the case of low saturation colours, 22 responses stated that the red bar was longer, three responses selected yellow as longer and 21 responses were that there was no difference.

Moreover, the results imply that the colour size illusion is influenced by the hues involved. Apparent size was compared across the six hue pairs and there was a significant difference in judgement [$\chi2(5) = 44.27$, $N = 576$, $p < 0.001$], but the saturation effect was not statistically significant.

4.2. *Identifying interventions that minimise colour illusions*

In this study, several levels of three interventions were tested to minimise the colour size illusion, but no conditions were found that had a statistically significant (α level 0.05) effect.

Highly saturated red and green were compared in five different levels of background brightness. The colour size illusion was observed in 15% to 25% of the responses, but the difference was not significant [$\chi^2(4) = 4.08$, $N = 240$, $p = 0.3959$].

In different levels of border colour, the colour size illusion was observed in 15% to 23% of the responses, but there was no statistically significant difference [$\chi^2(3) = 1.29$, $N = 192$, $p = 0.7324$] observed. The border colour of the target object was expected to delineate boundary information more clearly, allowing viewers to better judge the size of the object, but the results indicated no statistically significant border colour level that reduced the colour size illusion.

In the case of different levels of the background grid, the colour size illusion was observed in 19% to 25% of the responses, but once again there was no significant difference [$\chi^2(4) = 0.79$, $N = 240$, $p = 0.9395$] in the results. Even though the background grid brightness was expected to reduce the colour size illusion because the background grid would provide an additional cue assisting viewers to estimate the size of the targets, the experimental results failed to identify any statistically significant effect due to the level of background grid brightness.

4.3. *Further analysis on colour illusions*

To facilitate further analysis especially in terms of individual differences, the experimental data is illustrated in Figure 2. Participant number is displayed on the left and the number of errors by each participant displayed on the right. Each colour block indicates an experimental trial, with black representing a correct answer (no error) and each colour of the size illusion representing the colour that the participant selected as being longer. For example, the first participant made no errors in size judgement, while participant nine erred in all cases. The first four blocks for the fifth participant indicate that the participant answered three times that red was longer than yellow and once that that yellow was longer than red.

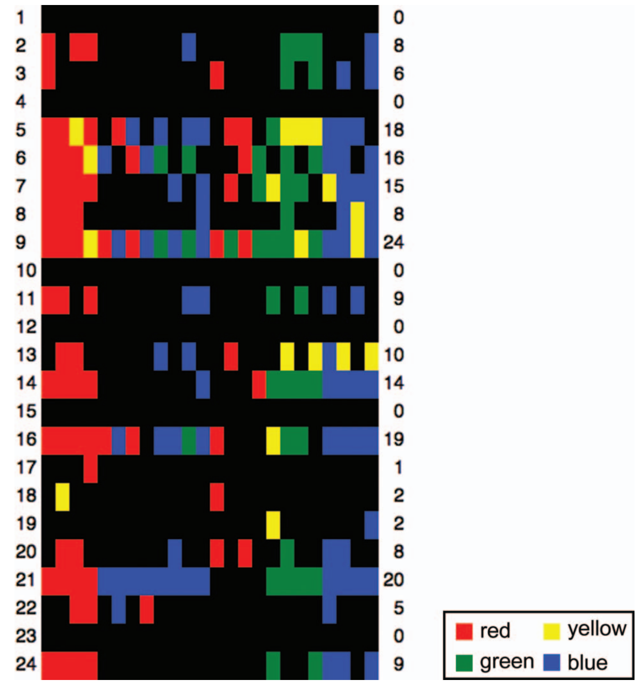

Figure 2. Visualisation of size judgement errors. Available in colour online.

The visualisation makes it easier to observe individual differences. Six participants made no errors, while 37.5% of participants made fewer than 10% size judgement errors (nine participants made less than three errors). However, almost 30% of the participants made errors in more than 50% of the trials (seven participants made more than 12 errors).

In addition to the individual differences, there is a clear pattern when yellow was one of the colours compared; focusing on the blocks including yellow, the other colours are noticeably more prevalent than yellow. For example, looking at the first four blocks, there are only four yellow blocks, which means that yellow was longer than red, while many others indicated that red was longer than yellow. Similar patterns can be observed in the last two groups of four blocks, comparing yellow with green and yellow with blue, respectively. Overall, this pattern of responses reveals a colour-size order in which yellow appears smaller than any of the other colours. Furthermore, more colours are present in each of these blocks, indicating that more errors were made when yellow was one of the colours being compared.

4.4. Decision-making difficulty

Participants were asked to rate the difficulty of making a judgement for each size judgement in order to reveal the influence of colour and interventions on user performance. It was expected that the information gathered would clarify how people suffer from difficulties with size judgement when colour is involved, and how interventions might be able to help them to judge size correctly and immediately. Further, it was expected that the interventions would not only reduce the illusion, but also would enhance performance on decision making by reducing the impact of factors that cause confusion.

A one-way ANOVA revealed that hue influenced size judgement difficulty, $F(5,570) = 2.63$, $p < 0.05$. Post hoc analysis using the Student's t-test on each paired comparison revealed that yellow-green ($M = 3.06$, $SD = 1.92$), yellow-red ($M = 3.0$, $SD = 1.92$), and yellow-blue ($M = 2.97$, $SD = 1.83$) comparisons were more difficult than red-blue ($M = 2.26$, $SD = 1.62$) comparisons (see Figure 3). In other words, participants perceived size judgement to be more difficult when yellow was involved in the pair or set.

4.5. Yellow and colour illusions

As discussed above, more illusions were observed when the colour yellow was involved and participants rated those size judgements as more difficult than other judgements. When yellow was compared to other colours, in this case red, blue and green, very few participants answered that yellow was longer than other colours. This result is inconsistent with the findings of a previous study (Tedford *et al.* 1977), in which yellow was perceived to be the second largest colour. It is possible that the choice of background colour explains this inconsistency; Tedford *et al.* used a gray background, but this study used a white background. Since yellow is not a primary colour in terms of the display mechanism of the TFT-LCD monitor used here it must be made by combining red and green, which may make it appear brighter than the other primary colours.

There are two possible explanations for these observations. First, the participants may have become confused by the boundary line. Since the saturated and bright yellow appears somewhat similar to the white background, participants may not have been able to distinguish the objects from the background. However, this does not explain why the yellow bars seemed shorter rather than longer. Moreover, green did not show a significant effect even though green had similar brightness to yellow (see L component in Table 1). More tests, such as a comparison of yellow bars with and without a border, are required to test this explanation.

An alternative and more plausible explanation is offered by the lateral inhibition theory (Hartline and Ratliff 1957, Arend 1993). Due to the bright white background, lateral inhibition reduces the perceived brightness of the yellow that is displayed, which may make the apparent size smaller than the actual size. Through the opponent process theory, this also explains why blue is estimated to be larger. According to the colour opponent-process theory, a yellow signal from long and medium cones in the viewer's eye can inhibit or excite the neural response of short cones, resulting in an underestimation or overestimation of

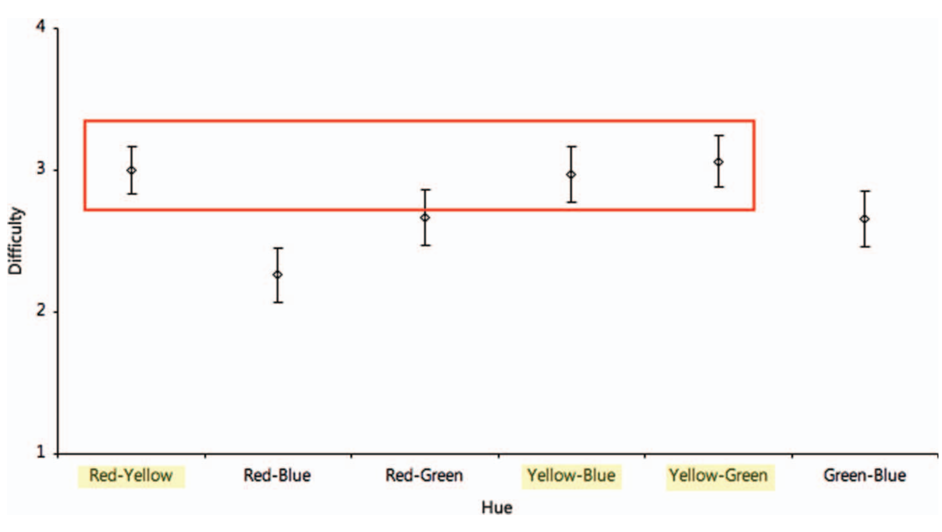

Figure 3. Subjective difficulty of size judgement.

blue. However, this explanation requires that lateral inhibition occurs before the opponent-processes affect colour perception. Further, this conjecture cannot explain why the judgements involving yellow were found to be particularly difficult until there is some evidence that the colour opponent process increases the human visual workload.

Since human colour vision is a complex system, more experiment data is needed to explain this phenomenon. For example, the results of experiments with several background colours and background images (containing known-coloured objects) could help explain this phenomenon by invoking the retinex theory (Land *et al.* 1983).

5. Discussion

5.1. Design guidelines

In this study, the tested interventions were not statistically significant in reducing the colour size illusion and although other implementations of those interventions might reduce the illusion, these are not yet feasible. Moreover, a thorough literature survey revealed no other design factor that has been found to reduce the colour size illusion. As a result, the first guideline is:

> *Consider the colour size illusion when using size and colour mapping together*

This is particularly relevant when size judgement is important. Colour coding for grouping or redundant coding would be effective, but designers should be careful when users must compare the size of different coloured objects. Especially on LCD monitors, designers should be careful using yellow for mapping on a white background, since yellow caused the most significant errors.

In many domains, the requirement to read the size of visualised objects is indispensable. When size judgement is critical, visualisation should not solely depend on human judgement and should provide additional information about size or size difference clearly. As a result, the second guideline is:

> *Provide additional size information with redundant codings*

For example, visualisation can group identically sized objects by using the same colour, since colour is good for categorisation (Mackinlay 1986). Figure 4a illustrates this approach. Another technique would be to present size differences explicitly with a reference line (Figure 4b). Visualisation can also utilise interaction techniques. For instance, when the user clicks on

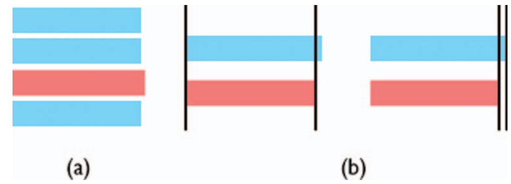

Figure 4. Examples of additional size information.

an object, a visualisation tool can highlight objects with the same size, or when the user selects multiple objects, then a visualisation tool can display information about size differences or size distribution. This additional information will help visualisation users to judge size accurately.

Colour coded information can be converted into other visual cues. In the case of nominal data, the information can be delivered by position, shape, length, angle or text (Mackinlay 1986). In the case of continuous data, visualisations have used saturation variation, brightness variation or hue variation (for example, from blue to red), although as earlier studies have shown that hue, saturation and brightness influence perceived size (Tedford *et al.* 1977), these mappings can be problematic. Furthermore, the literature suggests that coding on position, length, angle or volume is better than colour coding for quantitative data (Christ 1975, Cleveland and McGill 1984, Mackinlay 1986, Nowell *et al.* 2002).

6. Follow-up study

To verify the applicability and utility of the proposed recommendations, the guidelines were applied to a bioinformatics tool called the Genomic Sequence Viewer. Six examples were implemented and verified by interviewing domain experts (subject matter experts). Domain experts were asked their experience, whether they had suffered similar problems and evaluated each implementation. Detail descriptions of implementation with figures are available (Yoo 2007, p. 55–60). For this evaluation, mock-up images were presented on a web browser and both concerns and suggestions for each implementation were elicited. This semi-structured interview was conducted individually at the workplace locations of the domain experts.

Before discussing the follow-up experiment, here is a brief overview of the Genomic Sequence Viewer and curation process. The Genomic Sequence Viewer is a bioinformatics tool that is used to determine a genomic feature type and location based on the computed evidence of a given genomic sequence. Figure 5 is a screenshot of the Genomic Sequence Viewer, which shows multiple genomic features between 206617 basepair (bp) and 207929 bp. Each colour bar represents a predicted feature and each feature has a mouse-over interaction that shows detailed information such as predicted feature type, algorithm name, start position and end position. Figure 6 illustrates an example where the tFind algorithm is used to identify a tRNA, which starts from 207695 bp to 207768 bp. Researchers examine the analysed data by moving the mouse pointer over features or referring to the raw data table. If there is conflicting evidence and human judgement is required (as in the case shown in Figure 6), researchers follow the analysis process outlined in the *Standard Operating Procedures for Manual Nucleic Acid-Level Curation* (Snyder 2006), to make a decision.

6.1. Insights for design recommendations

The review by the domain experts provided some valuable insights into how the design recommendations can be utilised successfully in future bioinformatics visualisation tools. In this verification study, three main recommendations were evaluated.

The first tested design recommendation was that one should 'Avoid mapping on colour and size together'. Colours are widely used in the bioinformatics field; in certain applications colour coding is a domain specific population stereotype. For example, the Basic Local Alignment Search Tool (BLAST) uses colour coding to display E-values, which represent the significance of a result. However, the reviewers suggested that algorithmic information, encoded by colour in Genome Sequence Viewer, could be displayed using a different visual cue in many cases, thus avoiding the use of colour coding.

The second recommendation was that designers should 'Provide additional size information with other visual cues'. The expert reviewers unanimously agreed that displaying numbers was the most favourable approach. The reference line example also received a

Figure 5. Screenshot of Genomic Sequence Viewer.

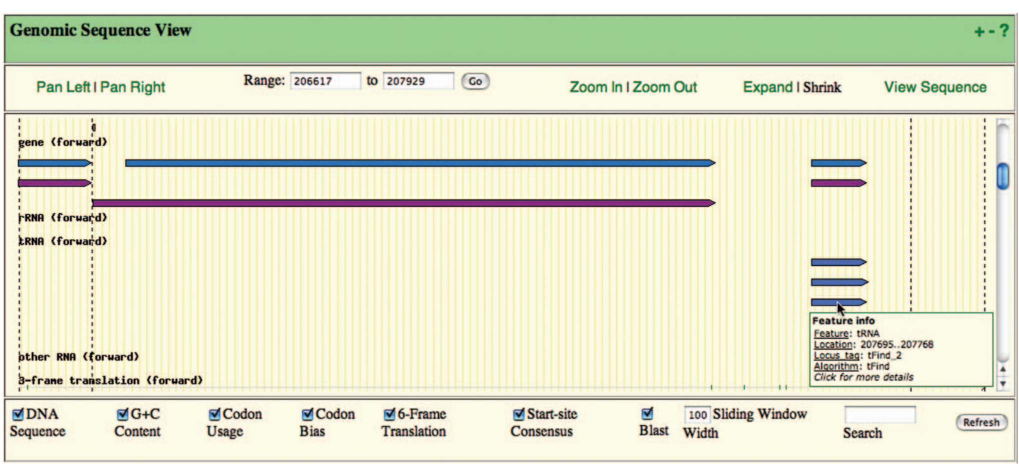

Figure 6. Mouse-over interaction of Genomic Sequence Viewer.

Table 2. Design guidelines.

Design recommendations	Reference
1. Consider the colour size illusion when you are using colour and size mapping together and size judgement is important.	Experiment result
(a) Try to avoid mapping on colour and size together, if possible.	No design factors known
(b) Convert the colour-coded information to other visual properties.	(Mackinlay 1986)
(c) Avoid using high saturated yellow on a white background when either size or depth is compared.	Experiment result
2. Provide additional information with redundant coding.	(Wickens and Hollands 1999)
(a) Provide additional size information with other visual cues such as text or reference line.	Follow-up experiment result
(b) Consider providing size information via interaction techniques or other alternatives.	Follow-up experiment result, (Tufte 1990)
3. Test the coloured visualisation, since the colour perception can be influenced by many factors.	Experiment result

positive evaluation, since it clearly shows even small differences, whereas 'colour coding for size' means that users must visually compare them. Redundant coding of size and size difference would be better. For example, reference lines make it possible for users to identify a difference, and exact numbers enable this difference to be determined precisely.

The last tested recommendation was that one should 'Consider providing size information via interaction techniques'. Interaction techniques received the most positive evaluations, since they allowed users to obtain detailed information when necessary. The reviewers stated that 'Being able to drag and see information about them is much more powerful, since it allows you [to] direct your interaction with it. On the other hand, you have more control over seeing the information', and 'I like the interactivity, since you are specifically selecting these to look at. You are restricting yourself just this block or just this small portion of interface, then I think, you can add a lot of information'.

In summary, although avoiding colour coding limits some options, it remains a very viable way of presenting information. Additional size information can be delivered using reference lines or exact numbers, but there are some trade offs. Selected information tailored to a specific task should be presented in the form of reference lines or exact numbers in order not to occlude other information. Redundant coding, incorporating both size and size differences, would be helpful. Interaction techniques are useful for many applications, since this approach does not occlude other information, and can provide very detailed context-specific information.

7. Conclusion

In this investigation of the influence of colour on perceived size, a series of colour pairs were used to demonstrate that the colour size illusion is significant. Furthermore, this study has uncovered an illusion pattern that is unique to a white background on an LCD monitor. In contrast to the findings of earlier studies, this study found that yellow made objects appear smaller than other colours. Two explanations of this phenomenon were proposed, but these will need to be strengthened with supplementary experimentation. Three types of interventions were tested to determine whether they minimised the colour illusion, but none were found to be statistically significant. Subjective ratings of the judgement difficulty of the choices revealed that yellow objects were particularly difficult for participants to assess.

Based on the experimental data and the accompanying literature survey, a set of design guidelines that could aid information visualisation are proposed here. First, this study found that it is better to avoid mapping colour and size together when the size is critical, as a significant size illusion was observed and the study was not able to identify any effective interventions to counteract this. For cases in which the visualisation maps both size and colour, the designer should provide supplementary information about either the size or size difference to enable users to easily determine the size information. Additionally, interaction techniques can be considered as alternative ways of providing size information.

Table 2 summarises the design recommendations for visualisations. These address the colour size illusions.

Proposed design recommendations were implemented in a bioinformatics tool and evaluated by domain experts and insights from these evaluations presented. Avoiding colour and size coding together is possible, but it suffers from severe limitations as colours are already used widely in the bioinformatics field. Additional size information can usefully be delivered using reference lines or exact numbers; having both size and size difference information is helpful, since users can see any differences immediately and precisely. The proposed interaction techniques were considered particularly useful by the reviewers as they do not occlude other information and can provide very detailed context-specific information.

The work reported here should be extended to understand the cause of the colour size illusion, particularly why yellow seems smaller on a white background. In this study, all the interventions were tested with a red-green pair. Comparing yellow with an obvious border line will reveal whether the errors were caused due to viewer confusion over the precise boundary location, while comparing yellow objects with various levels of background brightness will show whether it can be better explained by the lateral inhibition theory. This study can also be extended to evaluate a wide range of additional interventions, including background hue, background saturation, border width, border style (solid or dashed), background grid hue, background grid saturation, background grid width, background grid frequency, background grid style and background grid pattern (horizontal, vertical, or both).

Finally, the validation study was limited by the necessity to interview domain experts using only screenshot examples due to technical issues. Future reviews utilising working prototypes will make it possible to conduct more detailed evaluations.

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