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Penny J D'Ath initially read psychology at the University of Hertfordshire and worked as a research psychologist for a number of years in the NHS. She later retrained as an optometrist at City University and completed her pre-registration training at Moorfields Eye Hospital. Penny currently works as an optometrist and lecturer at City University, London.

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MEMORY FOR THE COLOR OF NON-MONOCHROMATIC LIGHTS

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ABSTRACT

Aims - To explore the limits of memory for the hue of colored illumination using non-spectral colors.

Methods - 84 undergraduate optometry students with normal color vision as assessed by the Ishihara 38 plate test, were given 10s to memorise the hue of a luminous surface (luminance $120cd.m^{-2}$), subtending 22 by 18 degrees in an otherwise unlit room. The sample hue was one of 12 samples with chromaticity spaced evenly every 30 degrees around a hue circle in the CIE UCS diagram. The circle, radius 0.06 was centred at the chromaticity of D65 (u'=0.198, v'=0.468). The hue was displaced randomly by between 40 and 100 degrees and the participants were required to use one of two keys to return the hue to its original appearance. The keys changed CIE 1976 hue angle (h_{uv}) by one degree, one in a clockwise and the other in a counterclockwise direction, but left the CIE 1976 saturation (s_{uv}) and the luminance unchanged. Each participant saw the to-be-memorised hue once only and made subsequent adjustments without seeing it again. Four adjustments were made immediately, four after one hour and a further four after one week. The second and the fourth in each set of four were preceded by a clockwise displacement of hue angle and the remaining two by an anticlockwise displacement.

Results -The CIE 1976 UCS chromaticity of the standard and the chromaticity of the very first adjustment performed immediately after the presentation of the standard were separated by 0.0210 (s.d. 0.0178) averaged across hues. One hue (purple) was more readily nameable than the others and was more accurately reproduced. There was no evidence of stable individual differences in observers' memory: observers' accuracy in reproducing one color was not significantly correlated with their accuracy in reproducing another. Adjustments made after an interval of one hour were worse than those undertaken immediately, but no better than those performed after one week.

The variability of hue memory under these conditions was similar to the variability of colored surfaces under common sources of illumination.

INTRODUCTION

Memory for colors is usually considered in relation to surface colors - colors of meaningless patches[1] or real objects[2 3] . Memory is influenced by how readily a color can be named, and how useful the name is in discriminating the color from others in the experiment[4]. Color memory is rarely measured under conditions in which the eyes have a chance to adapt to the color, as occurs when the colored light is used as a light source. Seliger[5], however, has obtained measurements of the ability of observers to remember and reproduce monochromatic light. He presented light from a monochromator for 0.2-3s, then changed the wavelength by at least 30-40nm and required observers to turn a knob to immediately reproduce the color. He measured the error in terms of the standard deviation in nanometers. The standard deviation varied with wavelength but was generally about twice the threshold at which one wavelength can be discriminated from another. When replotted in terms of the CIE UCS space, the standard deviation of the difference in chromaticities that can reliably be discriminated averages 0.0368 (s.d.=0.0224). The difference in chromaticity of a surface of uniform spectral reflectance under incandescent light (CIE Standard illuminant A) and under fluorescent light (CIE Type F2) is 0.0434 and between a fluorescent (F2) source and daylight (CIE Standard illuminant D65) is 0.0385. The largest such difference is between daylight and incandescent light (0.087). All these differences lie within 2 standard deviations of the difference in chromaticities that can reliably be discriminated. It would make sense in evolutionary terms if memory for the color of illumination has a precision appropriate for the variability with which changes in illuminant chromaticity are normally encountered. It seems plausible to expect the visual system to be insensitive to differences in illuminant color that are of little survival value, including differences that are typically "discounted" in order to maintain "color constancy". Seliger's measurements were undertaken using monochromatic light, and were therefore of maximum saturation and limited to spectral colors. The present study extended the measurements to non-spectral colors of low saturation in order to see whether memory for these colors was equally poor.

The study was motivated not only by a desire to determine the precision with which non-spectral colors can be remembered, but also in part by the effects of color on reading speed. It has been shown that at least 5% of the general school population read printed text more quickly with an optimal background color that is not white[6]. Certain individuals habitually wear colored glasses to improve reading speed and reduce visual stress[7]. In these individuals reading speed has been shown to increase when the text is illuminated with colored light. The reading speed decreases consistently with departures from optimal color, whether in respect of hue or saturation, and does so in a similar way from one individual to another. In general, there is little benefit of the color on reading speed, once the UCS chromaticity differs from optimum by a chromaticity difference of 0.076[7]. The question therefore arises as to the extent to which accuracy in the representation of the color of lighting within the visual system is playing a role in the measurement of the effects of colored light on reading speed, and the extent to which this is revealed by measurements of memory for the color of light.

METHOD

Apparatus.

A liquid crystal display (Flatron 4710B flatscreen) measuring 340mm horizontally by 270mm vertically was controlled by a program on a personal computer that used a look-up table based on interpolation between 42 points calibrated with a Minolta Chroma Meter II. It was possible to display any chromaticity on the perimeter of a circle in the CIE 1976 UCS diagram. The circle had a centre with chromaticity u'= 0.198, v'= 0.468 (that of CIE standard illuminant D65) and a radius of 0.06. In other words the display was of constant luminance and could vary in CIE 1976 hue angle (h_{uv}) without an associated change in the CIE 1976 saturation (s_{uv}). The luminance at the centre of the screen was 120 $cd.m^{-2}$, and it decreased toward the perimeter by no more than 20%. The computer program allowed the hue angle to be varied in a clockwise or anticlockwise direction at the touch of one of two keys. A single depression of a key changed the hue angle by one degree.

Participants.

31 male and 65 female undergraduate optometry students and staff at City University aged 18-44 years (mean 21) took part. All participants had normal color vision, as assessed by the Ishihara 38 plate test [8]. A subset of 60 participants undertook the experiment more than once, the trials separated by at least one week. The data for the second trial were considered separately.

Procedure. Each individual was seated at a distance of 0.84m from the screen in an otherwise darkened room, at which distance the screen subtended 22 by 18 degrees. They adapted to the darkened room for 5 min. They were then given 10s to observe and memorise the hue of the screen and were told they would be required to retain the color in memory for one week. The screen displayed one of 12 hues selected at random as the to-be-remembered color. The 12 hues were spaced 30 degrees apart on a hue circle in the CIE UCS diagram, as described above. The chromaticities are listed in Table 1.

Immediately following the 10s observation period the hue angle was displaced by between 40 and 100 degrees hue angle in a anticlockwise direction. The displacement was random, sampled with equal probability between 40 and 100 degrees. The change in color was instantanous. The participant was required to use the two keys until s/he was confident that the screen was once again displaying the original color, whereupon s/he pressed the space bar. The computer then changed the color, again by between 40 and 100 degrees but in the opposite direction to that previously used. Four such trials were completed. For trials 1 and 3 the displacement of color was anticlockwise on the hue circle and for trials 2 and 4 it was clockwise. After an interval of an hour, a further four such trials were undertaken, and these were repeated again after an interval of one week. The standard (to-be-memorised) color was presented once only at the outset of the trials. Participants saw only one color per trial lasting one week.

An additional 6 participants from City University, all female, aged 21-35 years (mean 27), were asked to observe the screen while they used the cursor keys to adjust the color of the screen so that it displayed the best example of each of the following colors: red, orange, green, blue, yellow, purple, pink. The colors were requested in the above order and the participants made four adjustments for each color in turn. Each of the 12 standard colors listed in Table 1 were then presented in clockwise order beginning with a hue angle of zero, then 330deg etc, and the participant was required to name the color, and to rate the acceptability of the name they had provided using a 7-point Likert scale (1=very poor; 7=very good).

RESULTS

Overall accuracy of naïve observers.

The mean errors (in degrees visual angle) with respect to sign for the first four settings were respectively +16.1, +2.3, +13.9 and +0.6. The initial setting was an "undershoot", in other words observers failed fully to restore the hue to its original value. Subsequent settings erred in the same direction, despite the fact that settings 2 and 4 were from a displacement that was in the opposite direction. This suggests that the first setting may have biased the remaining settings. The first setting that participants made, that immediately after the demonstration of the to-be-remembered hue, was not affected by previous settings. The following analysis was therefore conducted on this first setting. The data were obtained from 96 participants, a minimum of 7 per hue and a maximum of 9. The mean separation of the UCS chromaticities between the standard and the adjustment was 0.0210 (s.d. 0.0178) across participants and across hues. On the basis of the work of MacAdam and others[9], this corresponds to a difference of about 50 times the color difference that can just be discerned (i.e. about 50 jnds), although such interpretation must be qualified in view of the residual non-uniformity of the CIE 1976 UCS diagram.

Overall accuracy of the group.

Given that the settings of some participants erred in one hue direction and others in the opposite direction, the average hue difference with respect to sign between the standard and the very first setting gives an indication of how close the group as a whole came to replicating the standard immediately after it was shown. The mean was 16.8 degrees (s.d. 21.5), corresponding to a separation in UCS chromaticity of 0.0165 (s.d. 0.0211) between the standard and the group average. The color difference was in a clockwise direction from the standard, i.e. in a direction similar to that of the change in hue, suggesting that observers tended to underestimate the adjustment required.

Differences as a function of hue.

Since the direction of the error may have been influenced by the direction of the change of the hue, the data set was enlarged to include all the four settings that immediately followed the initial presentation of the sample. The absolute value of the error was calculated for each of the four settings per hue and averaged for each participant. The direction of the change of hue was balanced across settings and the average across settings better reflected the effect of the sample hue as opposed to the effect of both the sample hue and the change of hue. The mean errors are shown in Figure 1. One-way analysis of variance revealed a significant difference between hues ($F_{(11,84)}=2.46$, $p=0.01$). *Post hoc* comparisons using the method of Bonferroni revealed significant differences between 150 and 0 and 150 and 270 degrees.

Insert Figure 1 about here

A subsidiary study was undertaken in order to check whether the error scores were related to the ability to name the shade of color shown in the to-be-remembered sample. Six observers were asked to name each of the 12 colors shown and to rate the acceptability of the name they gave. The data in Figure 1 have been replotted in polar coordinates in Figure 2 and are shown by the continous curve. The length of the bold radial lines in Figure 2 is proportional to the number of participants (0-6) reporting their chosen name as acceptable. The longer the line the easier the shade of color was to capture in a color name.

Insert Figure 2 about here

As can be seen, the hue angle of 150 was difficult to name and difficult to remember. The hue angle of 270 was easy to name and easy to remember. However the hue angle of 0 was easy to remember but difficult to name, presumably because two alternatives (red and orange) were equally valid.

The six participants were asked to adjust the hue to create the best shade of red, orange, green, blue, yellow, purple, and pink. Around the perimeter of the figure are the ranges of hue angles (mean – 1sd to mean +1sd) of the settings. The setting for purple averaged 268 degrees and had the lowest standard deviation of the settings (6.7). This is consistent with the hue of 270 degrees being easy to name and remember. The setting for green was 73 degrees (sd 21) and for blue 208 degrees (sd 24) which might explain why 150 degrees (blue/green) is difficult to name and remember. The border between the settings for nominal "red" and "orange" lie close to 0 degrees, which might explain why this hue is difficult to name, but there remains the question as to why it is easy to remember.

Consistency within observers.

60 individuals were examined twice, more than one week apart, on each occasion with different hues, the hues usually spaced 60 degrees apart. Figure 3 shows the errors obtained by each individual on the two sessions. There is no significant correlation between the error on the two sessions (r=0.03), and therefore nothing to suggest that some individuals were consistently more accurate than others.

Insert Figure 3 about here

Stability over time.

The sample was presented once at the outset and the observer attempted to replicate its color four times at each of three occasions: immediately following the presentation, again after one hour and again after a week had elapsed. The mean of the absolute values of the errors on the four settings are shown as a function of time in Figure 4. The difference between immediate memory and that at one hour was highly significant ($t_{(113)}=5.7$, $p=0.000$) The difference between one hour and one week was not ($t<1$).

Insert Figure 4 about here

DISCUSSION

Participants were given the opportunity of immediately reproducing a color they had just seen but their ability to do so was more than 50 times worse than their ability to match colors that are simultaneously visible, according to the data of MacAdam [10]. Phillips [11] has shown that immediate memory for an arbitrary spatial configuration (of a random checkerboard, for example) is greatly impaired by the interpolation of a similar, but different, configuration, known as a mask. In the present work, the presence of a sample color different from that observers were required to remember presumably provided interference with sensory memory similar to that provided by a mask. The method of adjustment that was used here, though rapid, carried the disadvantage that the mask was variable.

The standard deviation of the chromaticity difference was 0.0178 and therefore similar to the figure of 0.0368 obtained by Seliger [5]. It is of interest that in both the present study and that of Seliger the standard deviation of the difference in color that can be discerned from memory (given an interpolated mask) is similar to the difference in the chromaticity of a white surface under different common sources of illumination. The difference in chromaticity of a white surface under incandescent illumination (CIE Standard Illuminant A) and under (CIE Standard Illuminant D65) is 0.0807 and this is likely to be the largest difference in light source chromaticity customarily experienced. It seems plausible to argue that the visual system is insensitive to differences in illuminant color that are of little survival value, including differences that are typically “discounted” in order to maintain “color constancy”.

In this respect it is of interest that the limits of memory performance obtained in the current study are close to the limits within which colors benefit reading speed. Wilkins and others[7] repeatedly measured reading speed under light of many different chromaticities in 5 individuals who habitually used colored lenses to aid reading. Reading speed varied reliably and systematically with chromaticity. There was an optimal chromaticity, different for each individual, at which reading speed was maximal, and reading speed decreased with departures from this optimum, whether in hue or saturation. A chromaticity difference of 0.076 was sufficient to remove most of the gain in reading speed that resulted at the optimal chromaticity. It seems unlikely that the effects of color on reading speed were cognitively mediated and resulted because participants had a “favourite” color that they remembered. Even if participants were to have remembered the color sufficiently well (which is most unlikely, given the retention intervals involved), they would also have had to have remembered the speed with which they read with that color. It seems more likely that the similarity between the limits on memory for color and the limits of the improvements in reading speed that color can confer both reflect the insensitivity of the visual system to differences in illuminant chromaticity under conditions of color adaptation.

Seliger[5] showed that the wavelength dependence of delayed matching of spectral colors exhibited the least variation at the same wavelengths as those reported for maximal color discrimination measured by bipartite wavelength matching, i.e. at the wavelengths of the intersections of cone spectral sensitivities. In the present study, the UCS space was used, and the differences in discriminability of stimulus colors have therefore been approximately equated. Non-spectral (unsaturated) colors were used, and this would have further reduced any differences due to cone spectral sensitivities. Unsurprisingly, the present data show no hue angle differences that are traceable to the intersection of cone spectral sensitivities.

ACKNOWLEDGEMENTS.

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REFERENCES

1. Perez-Carpinell, J., Camps, V. J., de Fez, M. D. & Castro, J. Color memory matching in normal and red-green anomalous trichromatic subjects. *Color Res. Appn* **26**, 158-170 (2001).
2. Perez-Carpinell, J., de Fez, M. D., Baldovi, R. & Soriano, J. C. Familiar objects and memory color. *Color Res. Appn* **23**, 416-427 (1998).
3. Bodrogi, P. & Tarczali, T. Colour memory for various sky, skin and plant colours: effect of the image context. *Color Res. Appn* **26**, 278-289 (2001).
4. Guest, S. & Van Laar, D. The effect of name category and discriminability on the search characteristics of colour sets. *Perception* **31**, 445-461 (2002).
5. Seliger, H. H. Measurement of memory of color. *Color Res. Appn* **27**, 233-242 (2002).
6. Wilkins, A. J., Lewis, E., Smith, F. & Rowland, E. Coloured overlays and their benefits for reading. *J. Res. Reading* **181**, 10-23 (2001).
7. Wilkins, A., Sihra, N. & Myers, A. Increasing reading speed using colours: issues concerning reliability and specificity, and their theoretical and practical implications. *Perception* **34**, 109-120. (2005).
8. Ishihara, S. *Tests for Colour-Blindness* (Kanehara Shuppan, Tokyo, 1970).
9. Wyszecki, G. & Stiles, W. S. *Color Science: Concepts and methods, quantitative data and formulae* (Wiley, New York, 1982).
10. MacAdam, D. L. Visual sensitivities to color differences in daylight. *Journal of Optical Society of America* **32**, 247-273 (1942).
11. Phillips, W. A. Short-term visual memory. *Philosophical Transactions of the Royal Society B* **302**, 295-309 (1983).

TABLE AND FIGURES

Table 1. Chromaticities of the standard (to-be-remembered) colors used in Experiment 1.

Hue (deg)	u’	v’
0	0.258	0.468
30	0.250	0.498
60	0.228	0.520
90	0.198	0.528
120	0.168	0.520
150	0.146	0.498
180	0.138	0.468
210	0.146	0.438
240	0.168	0.416
270	0.198	0.408
300	0.228	0.416
330	0.250	0.438

Figure Legends

Figure 1. Average error in degrees as a function of the sample hue.

Figure 2. The continuous curve shows the accuracy of reproduction of the sample from memory as a function of hue angle. The radius of the plot corresponds to 40 degrees hue angle. The lengths of the radial bold lines are proportional to the number of participants naming the hue with satisfaction. The length of the lines on the perimeter correspond to the range of settings (mean +/- 1 sd) of hue angle when participants were asked to set the hue to the color shown by the color name beside the line.

Figure 3. Mean absolute error in degrees hue angle on one trial plotted against the error on a second trial with different hue angle. The difference in hue angle between the two trials is shown in the legend. The data show a negligible and non-significant correlation ($r=0.03$).

Figure 4. Average error in degrees as a function of time.

Figures

Figure 1

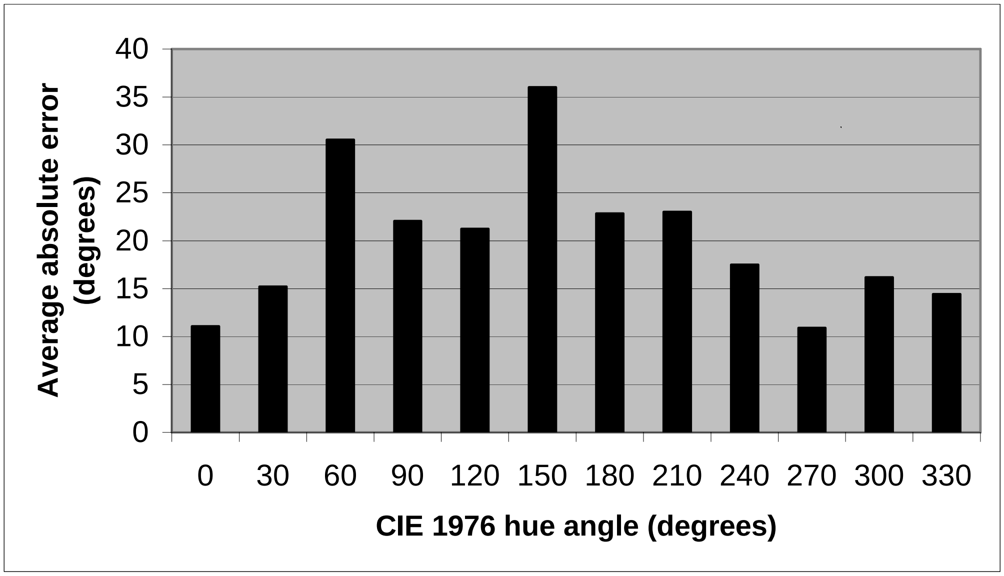


Figure 2

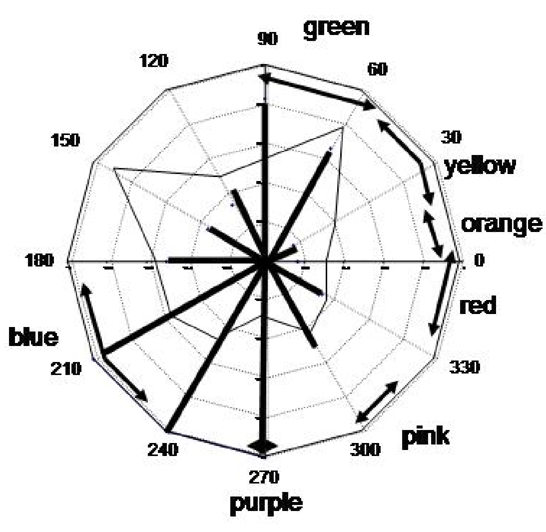
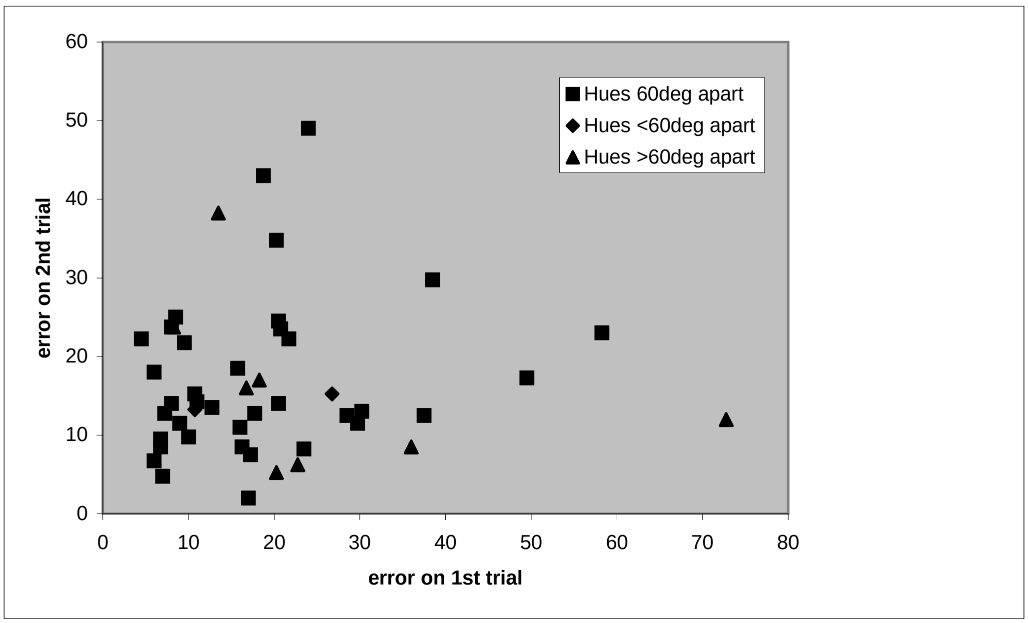
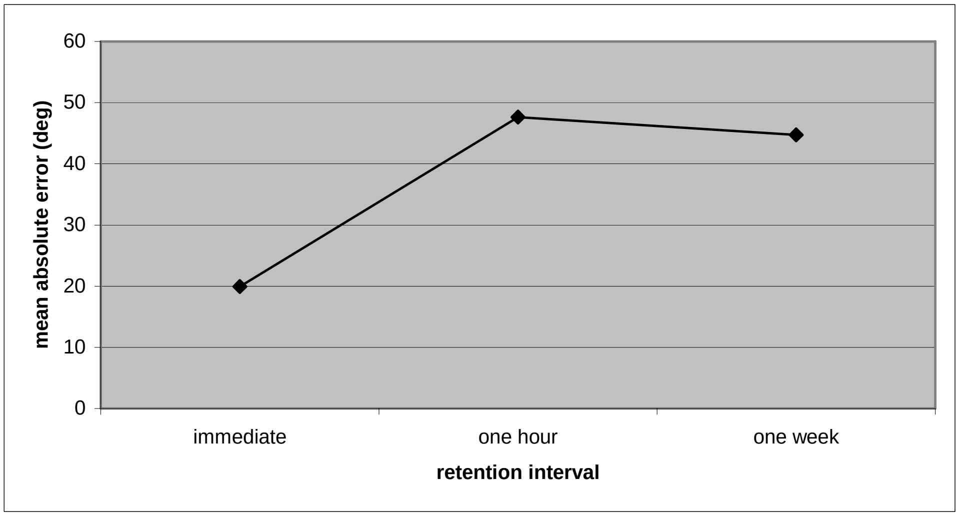


Figure 3



60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
error on 2nd trial
error on 1st trial
Hues 60deg apart
Hues <60deg apart
Hues >60deg apart

Figure 4


60
50
40
30
20
10
0
mean absolute error (deg)
immediate
one hour
one week
retention interval