1040-5488/90/6701-0003$02.00/0
OPTOMETRY AND VISION SCIENCE

Vol. 67, No. 1, pp. 3–7

Effects of Dioptric Blur on Snellen and Grating Acuity

FRANK THORN*
FAYE SCHWARTZ†
New England College of Optometry, Boston, Massachusetts

ABSTRACT

We compared the effects of dioptric blur on Snellen acuity and grating acuity. Dioptric blur had a strong negative effect on Snellen acuity, consistent with previous studies, but had little effect on grating acuity. Between 1 and 12 D both types of acuity were reduced as a linear function of blur. However, 12 D of blur reduced grating acuity to only 6/24 (20/80), whereas letter acuity was worse than 6/300 (20/1000). We suggest that these differences are due to the presence of "spurious resolution" in which phase-reversed gratings are readily detectable. But the phase reversals so distort the relative positions of linear segments within the letters that the letters become unrecognizable. These results indicate that Snellen letters are more sensitive than gratings to a patient's refractive errors, emphasize the differences between Snellen and grating acuity, and indicate that the minimum angle of resolution (MAR) concept is not applicable to letters.

Key Words: blur, refractive error, Snellen acuity, grating acuity, spurious resolution

Foveal vision has traditionally been tested by Snellen acuity or some other optotype test.[1] Recently, other techniques such as grating acuity have been advocated for special clinical situations. The application of grating acuity ranges from gratings being used to test acuity in infants[2,3] to gratings generated by interference fringes being used to test foveal vision in cataractous eyes.[4,5] Despite the obvious differences between letter and grating acuity, these measures are often treated as if they were interchangeable. A MAR can be calculated for both tests and the MAR's for normal subjects are approximately equal for the two. Many assume that both tests are also limited by resolution in a similar manner. However, we will show that the resolution limits of the two tests must involve very different mechanisms because dioptric blur influences them so differently.

Presented at the Annual Meeting of the American Academy of Optometry, Atlanta, Georgia, 1986.
Received June 17, 1988; revision received July 27, 1989.
* Optometrist, Ph.D., Member of Faculty.
† Optometrist.

Previous studies have shown that the detection of gratings is a very different task than the recognition of Snellen letters. For example, strabismic amblyopia induces a mild loss in contrast sensitivity and grating acuity relative to more serious losses in Snellen and vernier acuities. The Snellen and vernier acuity losses correlate well with each other but poorly with grating acuity.[6,7] It is also known that Snellen acuity falls off more quickly than grating acuity in the eccentric visual field.[8] In addition, luminance is known to have a different effect on grating acuity than on Landolt C acuity. Grating acuity is better at low luminances but asymptotes at about 100 Td, whereas Landolt C continues to improve up to luminances of 10,000 Td.[9]

Conceptually it is convenient to assume that maximum grating acuity for an infinitely extended grating is a pure resolution-limited detection task. In a carefully designed experiment smaller gratings may approach this standard. Thus, grating acuity should be strongly affected by optical blur in a relatively straightforward manner. Green and Campbell[10] in their classic paper have shown that blur decreases contrast sensitivity for gratings, especially for the high spatial frequencies that approach the grating acuity cutoff. However, the decreases at even the highest spatial frequencies appear to be too slight to cause the decreases generally described for Snellen acuity; for example, when in focus their subjects had acuities of about 45c/deg [analogous to 6/3.9 (20/13) Snellen acuity]. One diopter of blur reduced acuity to about 40 c/deg (6/4.5, 20/15) and two diopters of blur reduced acuity to about 25 c/deg (6/7.2, 20/24).[10] These differences are trivial compared to the losses that dioptric blur induces in Snellen acuity.[1,11] Recently, Powers and Dobson reported that infants' grating acuity is virtually unaffected by blur. In addition, they showed that 6 and 14 D lenses had a surprisingly small effect on the grating acuity of 10 adults.[12]

Snellen acuity is a far more complex task than grating acuity. It is based on recognition but obviously letters cannot be recognized unless the lines within them can be resolved. Thus, Snellen acuity must be resolution dependent. However, more than resolution is needed. Westheimer has suggested that hyperacuity is also needed to detect the relative positions and orientations of the lines contained in letters.[13] It is well known that both vernier acuity for two features that are properly separated and displacement hyperacuity are insensitive to blur.[14-16] For our purposes it is more important to remember that vernier acuity for small adjacent features, like those in letters, is highly sensitive to blur.[14] In addition to feature resolution and position sensitivity, a patient must then match letters with memory in order to recognize and name them.

We are left with the dilemma that grating and Snellen acuities are often treated as interchangeable resolution-limited tasks. Yet they differ in a number of identifiable ways. Their relation to dioptric blur is especially confusing, perhaps even paradoxical, because dioptric blur seems to have a greater effect on the multifaceted Snellen acuity task than on the simple resolution-limited grating acuity task. Thus, we have designed this experiment to examine the relation between dioptric blur over a 12 D range and these two types of acuity.

METHODS

Subjects

Seven optometry students between 22 and 27 years of age, with 6/6 (20/20) or better corrected acuity and normal binocularity, acted as subjects. Their refractive errors ranged between +1.00 and −5.00 D equivalent sphere with 0.50 D or less cylindrical component.

Stimuli

Slides were projected onto a matte white screen by a Kodak Carousel Projector. A large visual field was used for the gratings so that when the subjects were instructed to fixate toward the center of the field, aliasing artifacts due to interactions between the grating stripes and the edge of the field could be minimized. Grating slides were provided by the M.I.T. Infant Vision Laboratory. The slides had square wave gratings and were masked to provide a 10.7° circular field. Two types of letter acuity displays were used. Both were made from displays containing a row of eight Helvetica rub-on letters. The letters were either separated in a manner similar to the interletter spacing of letter acuity charts or were crowded together in a manner that is known to disrupt letter recognition in other contexts. Interletter spacing for normal letters equaled 1.0 letter width but was reduced to 0.25 letter width for crowded letters. The full line of 8 letters was shown for 6/4.2 (20/14) to 6/120 (20/400) letter sizes. With larger letters 6/180 to 6/480 (20/600 to 20/1600), fewer letters were visible on the screen. The light bars in the gratings and the illuminated background for the letters had luminances of 25 cd/m^2 and contrast exceeding 0.80.

Procedure

Subjects viewed the screen monocularly from 6 m (20 ft) in a dark room. Trial lenses were worn directly over their habitual corrections in trial lens clips or in trial lens frames if the subject did not wear eyeglasses. Plus lenses of 0, 1, 2, 4, 6, 8, and 12 D were used in random order. Acuity was tested for each level of blur by a modified method of limits with first a descending and then an ascending sequence. Gratings were presented at 1 of 3 orientations, vertical, 30° left, or 30° right in random order. Subjects were instructed to look at the center of the grating and were required to report the orientation of the grating. Eight trials were presented for a given frequency. Frequencies were increased until at least four trials were missed. Eight more trials were then presented at this frequency and frequencies were increased until the subject correctly identified the orientation on all eight trials. Snellen letters were presented in rows of 8 letters in order of decreasing size until 75% or more were missed. Then they were presented in increasing size until 100% accuracy was achieved.

The probability of detecting the 16 gratings or Snellen letters accurately at each frequency or size was plotted on probit paper and fitted with a straight line by eye. A 75% probability-of-seeing criterion was used as our acuity measure in each case. Thus, the procedure and criteria were closely matched for grating and letter acuity tasks.

RESULTS

Grating acuity is affected very little by dioptric blur. Two diopters of blur reduces acuity from 30 c/deg (analogous to 6/6, 20/20) to 15 c/deg (6/12, 20/40). Twelve diopters reduces it to about 7.7 c/deg (20/80). However, the blurred gratings appear very unstable. Looking through the lenses slightly off axis or changing the blur by as little as 0.50 D can cause unexpected increases or decreases in contrast as well as horizontal movement of the lines in the grating relative to the screen.

On the other hand, Snellen acuity is drastically affected by blur. Two diopters reduces acuity from 6/6 (20/20) to about 6/36 (20/120). Twelve diopters reduces acuity below 6/300 (20/1000). There was no significant difference between the effects of blur on crowded and uncrowded letters. The data are plotted on a logarithmic scale, as recommended by Westheimer,[17] in Fig. 1. On the logarithmic scale standard deviations are independent of acuity. The data are also plotted on a linear scale, which shows the linear relation between blur and acuity and the large difference between grating acuity and Snellen acuity (Fig. 2).

DISCUSSION

Our results show that blur has a dramatically different effect on letter reading acuity than it does on grating acuity. Snellen acuity is markedly reduced by blur with an almost linear relation between letter size and blur. The normally calculated MAR of letters increases at a rate of about 4.4 min/D. These results are consistent with previous findings.[1,14] We were surprised that crowded letters

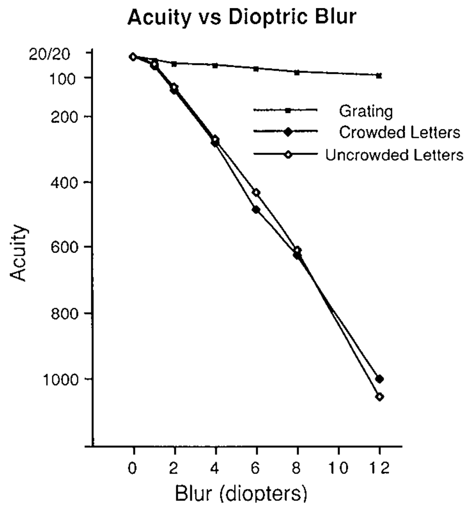

Figure 1. The effect of dioptric blur on three measures of visual acuity with acuity plotted on a logarithmic scale. Error bars represent standard deviations.

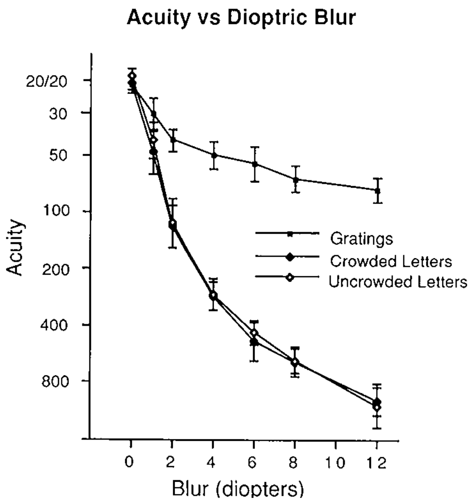

Figure 2. Same data as in Fig. 1 plotted on a linear scale.

were not affected more by blur than uncrowded letters. Hohmann and Haase[18] and Thorn[19] have shown that this amount of crowding can significantly reduce the acuity of 5- to 8-year-old children. Bouma[20] and Geiger and Lettvin[21] have shown that crowding of capital letters can reduce letter recognition with eccentric fixation. Because the blur used in our study would cause the luminance distribution within the almost adjacent edges of crowded letters to spread into each other, we thought this might also make resolution and orientation discrimination of the lines within the crowded letters more difficult. Our results indicate that the within-letter features are blurred into illegibility in the central vision of adults before the between-letter features blur together. Thus, there is no blur-related crowding effect.

Dioptric blur has relatively little effect on the detection of gratings. The relation between grating line width and dioptric blur is only 0.25 min/D in this study. This is consistent with the findings of Green and Campbell.[10] Small amounts of blur significantly reduce the apparent contrast of the gratings but additional amounts have little effect on their appearance. The observation that the contrast and position of the lines in a grating seem to change when the lens is moved horizontally before the eye is important because it indicates that the phase of just visible blurred gratings is unstable.

We believe that the gratings are visible but unstable due to the nonmonotonic shape of the optical modulation transfer function of the eye.[22-25] Dioptric blur reduces the contrast of gratings at higher spatial frequencies until the contrast is reduced to zero. At frequencies just above this zero point contrast is negative, indicating that a modulated image is on the retina but its phase is reversed. The contrast vs. blur function oscillates between positive and negative at higher frequencies with the peak contrast of each reversal decreasing (Fig. 3). Thus, the phase of some Fourier components of a grating might be correct, whereas others might be reversed. These phase changes can be very labile. The modulation transfer of frequencies above the first zero point is termed spurious resolution.

Smith used the principles of geometric optics to calculate functions relating the modulation transfer function's zero points to the amount of blur for mid and low spatial frequencies.[25] He used Levi's calculations[26] based on physical optics to show this relation for high spatial frequencies. The spatial frequencies of the first 4 zero points of an aberration-free eye with a 3.5 mm pupil and 550 nm light are shown as a function of dioptric blur in Fig. 4. This is the expected pupil diameter when viewing a surface with a luminance of approximately 25 cd/m^2. At mid and low spatial frequencies the theoretical zero points show that spatial frequency is an inverse function of dioptric blur. At higher spatial frequencies these curves turn upward predicting infinite spatial resolution at zero diopters of blur, an obvious impossibility in the real world. In fact, the theoretical zero point functions include two

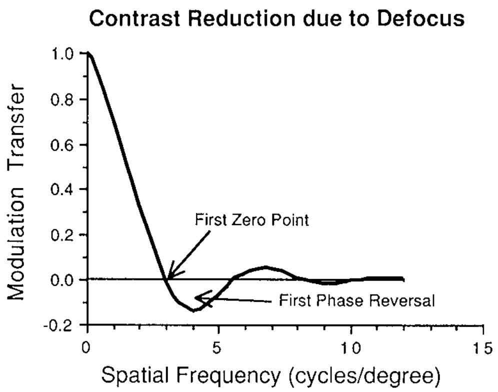

Figure 3. The modulation transfer function of the eye with about 3.00 D of blur. Note the alternating phase reversals at higher spatial frequencies.

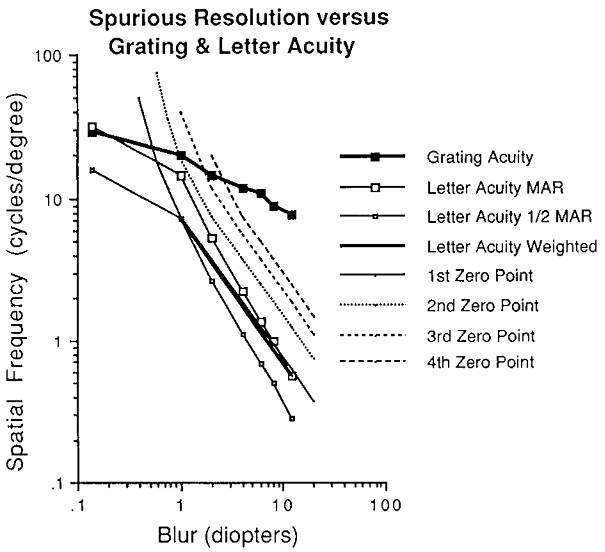

Figure 4. The spatial frequencies of the first four contrast zero points are inversely proportional to blur for most frequencies (first zero point, ———; second zero point, · · · · · ·; third zero point, ------; fourth zero point, — — —). The calculated MAR for gratings is well above the first zero point for blur in excess of 1.00 D. The calculated MAR and ½ MAR functions straddle the first zero point for all but clear viewing conditions. The weighted average of these two functions is just within the region free of spurious resolution.

unrealistic assumptions, first that the eye is an aberration-free system and second that only 550 nm light is used. If we assume normal ocular aberrations and white light, the zero point functions will flatten down so that the first zero point asymptotes at about 70 c/deg with minimal refractive error.

When the grating acuity data or the uncrowded letter acuity MAR data are superimposed on the calculated functions of Smith,[25] most of the data points fall in the region of spurious resolution. Only with zero diopters of blur do the data points for both types of acuity fall well within the region that is free from spurious resolution even when aberrations and broad spectrum light are considered. It should be noted that acuity with clear vision is worse than would be predicted from the rest of the acuity curves. Both acuities are about 30 c/deg with minimal dioptric blur. This is because the resolution of an optically corrected eye is limited by neural factors such as the foveal cone mosaic rather than by optical factors. This should limit acuity to about 40 c/deg. In addition, the finest gratings and letters in this study (<6/6, 20/20) had slightly less contrast than all the other stimuli, further reducing the acuity of correctly refracted subjects.

With as little as 1 D of blur, grating acuity data fall well within the region of spurious resolution. With 4 D or more blur our subjects must use spurious resolution above the fourth zero point of the optical modulation transfer function. Although the gratings have unstable phase and contrast, which makes them noticeably different from slightly blurred gratings, this does not disrupt the ability of subjects to detect the presence and orientation of the spurious gratings. In fact, subjects achieve surprisingly high acuities. We believe that spurious resolution also explains the results of Green and Campbell[10] and Powers and Dobson.[12]

Letter acuity data have a very different relation to dioptric blur. With 2 to 12 D of blur, the uncrowded letter acuity data based on normal calculations of MAR fall close to the first zero point, although only the data point for the greatest amount of blur (12 D) falls within the region free of spurious resolution. This MAR calculation assumes 2.5 c/letter (i.e., 3 dark bars and 2 light bars in the vertical meridian of the letter E). However, most letters do not have major Fourier components at such high frequencies. On the other hand, most letters do contain important Fourier components at lower frequencies that approach 1 c/letter.[27] Therefore, we have also shown a function for letter acuity based on ½ MAR vs. dioptric blur. For large letters such as the 6/360 (20/1200) letters seen with 12 D of blur the MAR is calculated to be 60 min arc. This represents such a low spatial frequency (0.5 c/deg) that the lower Fourier components would make little contribution to letter identification and those near the calculated MAR would provide the most information. Thus, the recognition of such large letters must be based primarily on frequencies approaching normally calculated MAR's. For small letters such as the 6/12.9 (20/43) letters with 1 D of blur, the normally calculated MAR is about 2.1 min arc (13 c/deg). These fine Fourier components are not as close to the peak of the contrast sensitivity function as the lower components (6.5 c/deg). Thus, lower frequency components (approximately ½ MAR) would be most readily used to identify small letters. For letters of intermediate size all Fourier components would be used in letter identification with the weighting of components dependent on letter size. We have shown this weighted letter acuity function in Fig. 4 as a linear function connecting ½ MAR at 1 D with MAR at 12 D of blur. This function is parallel to the first zero point curve and is just within the region free of spurious resolution for all levels of blur. This suggests that letters are recognizable only if the spatial components used for recognition are free of spurious resolution or phase reversals.

This analysis indicates that the MAR concept is not applicable to letters. In fact, calculating the effective MAR for each letter under each level of blur with each viewing condition for each subject is unrealistically difficult. It is simply fortuitous that the normally calculated MAR of letters and gratings are so similar (≤1 min) for normal best-corrected observers. The effective MAR for fine letters may be less than half the calculated MAR because normal subjects may use lower Fourier components for letter recognition.

Why must the effective Fourier components of letters be in phase with each other for a letter to be recognized? Spurious resolution may allow the details of Snellen letters to remain visible but the relations between the lines within the letters may be thoroughly confused. Vernier acuity for stimuli with short segments (<10 min) and close proximity between segments (<2 min) is also very sensitive to blur.[14,15] Thus, even though many of the details in a slightly blurred letter can be detected, the loss in fine position localization may totally disrupt a subject's ability to recognize the orientation or shape of a line within a letter or its relation to other line segments within the letter.

It is clear that neither grating acuity or Snellen acuity are simple tests of visual function. Grating acuity allows an observer to perform a detection task using spuriously resolved patterns which cannot effectively contribute to the recognition of complex patterns such as letters and words. Letters have spatial characteristics that are so complex that an examiner cannot define the spatial components actually used by an observer. These are two very different tasks, each of which provides useful information that cannot be provided by the other.

On a practical clinical level, the fact that grating visibility is affected so little by blur indicates that a grating is not a good visual display for a refraction. However, it suggests that this may be an excellent target for testing the visual system through compromised optics. For example, several devices are now used to predict the postsurgical acuity of patients with cataracts or other types of ocular problems by presenting interference fringes on the retina or projecting gratings onto the retina with Maxwellian view. But optical tricks such as interference fringes and Maxwellian view may be only one factor in the ability of these patients to detect these acuity displays. The intrinsic characteristics of gratings as a test target may be just as important a reason for these devices showing better acuity than Snellen acuity and may also explain why they are such poor predictors of postsurgical Snellen acuity.[28-32]

ACKNOWLEDGMENTS

We thank James P. Comerford, Joseph A. Bauer, and Glen McCormack for their helpful comments. This research was supported by the New England College of Optometry.

REFERENCES

1. Sloan LL. Measurement of visual acuity: a critical review. Arch Ophthalmol 1951;45:704–25.
2. Teller DY, Morse R, Borton R, Regal D. Visual acuity for vertical and diagonal gratings in human infants. Vision Res 1974;14:1433–9.
3. Gwiazda J, Brill S, Mohindra I, Held R. Infant visual acuity and its meridional variation. Vision Res 1978;18:1557–64.
4. Green DG. Testing the vision of cataract patients by means of laser-generated interference fringes. Science 1970; 168:1240–2.
5. Cavonius CR, Hilz R. A technique for testing visual function in the presence of opacities. Invest Ophthalmol 1973;12:933–6.
6. Levi DM, Klein S. Differences in vernier discrimination for gratings between strabismic and anisometropic amblyopes. Invest Ophthalmol Vis Sci 1982;23:398–407.
7. Levi DM, Klein S. Vernier acuity, crowding and amblyopia. Vision Res 1985;25:979–91.
8. Levi DM, Klein S, Aitsebaomo AP. Vernier acuity, crowding and cortical magnification. Vision Res 1985;25:963–77.
9. Schlaer S. The relation between visual acuity and illumination. J Gen Physiol 1937;21:165–88.
10. Green DG, Campbell FW. Effect of focus on the visual response to a sinusoidally modulated spatial stimulus. J Opt Soc Am 1965;55:1154–7.
11. Hirsch MJ. Relation of visual acuity to myopia. Arch Ophthalmol 1945;34:418–21.
12. Powers MK, Dobson V. Effect of focus on visual acuity of human infants. Vision Res 1982;22:521–8.
13. Westheimer G. Visual acuity and hyperacuity. Invest Ophthalmol Vis Sci 1975;14:570–2.
14. Enoch JM, Williams RA. Development of clinical tests of vision: initial data on two hyperacuity paradigms. Percept Psychophys 1983;33:314–22.
15. Westheimer G. The spatial sense of the eye: Proctor Lecture. Invest Ophthalmol Vis Sci 1979;18:893–912.
16. Nakayama K, Silverman GH. Detection and discrimination of sinusoidal grating displacements. J Opt Soc Am A 1985; 21:267–74.
17. Westheimer G. The scaling of visual acuity measurements. Arch Ophthalmol 1979;97:327–30.
18. Hohmann A, Haase W. Development of visual line acuity in humans. Ophthal Res 1982;14:107–12.
19. Thorn F. Letter reading loss in children when Snellen letters are crowded together. Paper presented at the Meeting of the American Academy of Optometry, 1986.
20. Bouma H. Interaction effects in parafoveal letter recognition. Nature 1970;226:177–8.
21. Geiger G, Lettvin JY. Enhancing the perception of form in peripheral vision. Perception 1986;15:119–30.
22. Westheimer G. Pupil size and visual resolution. Vision Res 1964;4:39–45.
23. Charman WN, Jennings JAM. The optical quality of the monochromatic retinal image as a function of focus. Br J Physiol Opt 1976;31:119–34.
24. Charman WN, Tucker J. Dependence of accommodation response on the spatial frequency spectrum of the observed object. Vision Res 1977;17:129–39.
25. Smith G. Ocular defocus, spurious resolution and contrast reversal. Ophthal Physiol Opt 1982;2:5–23.
26. Levi L. Handbook of Tables of Functions for Applied Optics. Cleveland: CRC Press, 1974.
27. Ginsburg AP. Visual information processing based on spatial filters constrained by biological data. (AMRL-TR; 78–129) Wright-Patterson Air Force Base, OH: Aerospace Medical Res Lab, Air Force Systems Command, 1978.
28. Bloom TD, Fishman GA, Traubert BS. Laser interferometric visual acuity in senile macular degeneration. Arch Ophthalmol 1983;101:925–6.
29. Faulkner W. Predicting acuities in capsulotomy patients: interferometers and potential acuity meter. J Am Intraocul Implant Soc 1983;9:434–7.
30. Fish GE, Birch DG, Fuller DG, Straach R. Retinal function testing in eyes with known maculopathy. Invest Ophthalmol Vis Sci 1985;26(Suppl):308.
31. Spurny RC, Zaldivar R, Belcher CD, Simmons RJ. Instruments for predicting visual acuity: a clinical comparison. Arch Ophthalmol 1986;104:196–200.
32. Goldstein J, Jamara RJ, Hecht SD, Liberace AR, Collins KM. Clinical comparison of the SITE IRAS hand-held interferometer and Haag-Streit Lotmar visometer. J Cataract Refract Surg 1988;14:208–11.

AUTHOR'S ADDRESS:
Frank Thorn
New England College of Optometry
424 Beacon Street
Boston, Massachusetts 02115