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Reduced visual acuity is mirrored in low vision imagery

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Research has examined the nature of visual imagery in normally sighted and blind subjects, but not in those with low vision. Findings with normally sighted subjects suggest that imagery involves primary visual areas of the brain. Since the plasticity of visual cortex appears to be limited in adulthood, we might expect imagery of those with adult-onset low vision to be relatively unaffected by these losses. But if visual imagery is based on recent and current experience, we would expect images of those with low vision to share some properties of impaired visual perception. We examined key parameters of mental images reported by normally sighted subjects, compared to those with early- and late-onset low vision, and with a group of subjects with restricted visual fields using an imagery questionnaire. We found evidence that those with reduced visual acuity report the imagery distances of objects to be closer than those with normal acuity and also depict objects in imagery with lower resolution than those with normal visual acuity. We also found that all low vision groups, like the normally sighted, image objects at a substantially greater distance than when asked to place them at a distance that 'just fits' their imagery field (overflow distance). All low vision groups, like the normally sighted, showed evidence of a limited visual field for imagery, but our group with restricted visual fields did not differ from the other groups in this respect. We conclude that imagery of those with low vision is similar to that of those with normal vision in being dependent on the size of objects or features being imaged, but that it also reflects their reduced visual acuity. We found no evidence for a dependence on imagery of age of onset or number of years of vision impairment.

Mental visual imagery plays an important role in several aspects of human cognition, including navigation (Chersi, Donnarumma, & Pezzulo, 2013; Schinazi, Thrash, & Chebat, 2016), visual memory capacity (Keogh & Pearson, 2014), problem-solving (Hegarty & Kozhevnikov, 1999; Shaver, Pierson, & Lang, 1974), and creativity (LeBoutillier & Marks, 2003). It is also a widely used tool in psychotherapy (Lusebrink, 1990; Pearson, Naselaris, Holmes, & Kosslyn, 2015).

While there has been a decades-long debate about whether visual images as represented in the brain are fundamentally descriptive (Pylyshyn, 1973, 1981, 2003) or pictorial in nature, recent neuroimaging evidence showing commonalities between visual imagery and the low-level neural substrate of visual perception has favoured a view of

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visual imagery as having a depictive nature – of recalling weaker versions of perceptual images (see review in Pearson & Kosslyn, 2015). The findings we report below show some striking differences in the imagery of those with normal and low vision (i.e., impaired but functional vision), and these tend to, but do not unequivocally support, a characterization of visual imagery as depictive. We do not intend to weigh in strongly on the complex issues underlying the imagery debate. Our central purpose is to outline how imagery is impacted by low vision.

The term 'low vision' has been defined in numerous ways (Leat, Legge, & Bullimore, 1999), but here we are referring to those who have significantly reduced visual acuity that cannot be corrected by ordinary corrective lenses, and/or those with visual fields restricted by retinal diseases including retinitis pigmentosa and glaucoma.

As background to the current paper, three earlier studies using congenitally blind subjects who have little or no visual experience have suggested that the nature of imagery depends on prior sensory experience. Arditi, Holtzman, and Kosslyn (1988) found that unlike sighted subjects, who report imaging large objects more distantly than small objects, congenitally blind subjects tend to image objects at distances within or very close to arms' reach irrespective of their size, suggesting that objects are represented haptically in this population. Similarly, unlike sighted subjects, congenitally blind subjects do not show evidence of representing more distant objects as smaller, as they would if they were relying on a retinotopic representation; nor do they point at the two ends of imaged objects at decreased pointing angles with increased distance as do those with normal vision. Finally, the distances of objects in imagery are adjusted by sighted subjects in order to 'fit' into a two-dimensional field of limited extent, but blind subjects' images show no similar tendency to adjust imaged distances to avoid 'overflow' of the space in which objects are depicted in imagery perhaps analogous to the visual field in active viewing.

Vanlierde and Wanet-Defalque (2005), using nearly identical methodology, replicated and extended the Arditi et al. (1988) findings, showing that only the imagery of those blinded prior to age three but not those blinded after age six, differed qualitatively from those of a sighted control group. Their data also showed that those blinded after age six imaged objects at closer distances than the sighted group, but more distantly than the early blind group, suggesting that visual experience strongly determined spatial properties of the mental imagery of those blinded later in life.

Finally, Hollins (1985), using a method that assessed the degree of pictorial and nonpictorial imagery subjects could use in an imagery problem-solving task, found that the proportion of life that subjects had been blind was related in part to the degree to which they employed pictorial imagery in the task, suggesting that the nature of visual imagery itself depends on visual experience.

In a 2003 *New Yorker* article, Sacks (2003) described remarkable differences in the imagery reported by three blind individuals. These reports ranged from the highly preserved sense of spatial imagery of a man blinded in an accident at age 21 to the decline and disappearance of visual imagery experienced by author and religion scholar John Hull (Sacks, 2003). Sacks remarked on the wide individual differences in imagery associated with blindness among these three individuals, and also on evidence for large individual differences in imagery among people with normal sight.

Studies examining visual imagery in those with limited visual fields due to homonymous hemianopia (Farah, Soso, & Dasheiff, 1992; Gbadamosi & Zangemeister, 2001; Kosslyn, Cave, Cronin, Arditi, & Gabrieli, unpublished data) also suggested that imagery field extent may be reduced (and shifted horizontally) in those with visual fields of more limited extent, also suggesting that perceptual experience shapes the spatial properties of imagery.

Normal vision and complete blindness can be seen as two ends of a continuum that could form or limit the basis of imagery, where visual experience is or is not an available perceptual substrate. Low vision is an intermediate case, which our study addresses. We ask here how having low vision impacts mental imagery, and what if any are the effects on imagery of acquiring low vision early rather than later in life? Does the mental imagery of those with visual impairment reflect the extent of their acuity and/or field loss? Do those with low vision employ imagery with increased magnification needs and reduced visual resolution or reduced visual fields? We explored the spatial properties of the visual images of a sample of this population.

Imagery has been studied using brain imaging and novel applications of behavioural methods such as binocular rivalry (both are reviewed in Pearson, 2014) in which a pattern vividly imaged tends to dominate in a rivalrous dichoptic display. However, for our purposes, we selected methods that could be directly compared to the literature on imagery in both sighted and blind subjects. Since imagery strength (measured behaviourally) has been reported to be directly related to prefrontal cortex surface area (Bergmann, Genç, Kohler, Singer, & Pearson, 2016), we included a measure of imagery vividness in our questionnaire. We did not have the opportunity to assess anatomical aspects of our subjects, for which other aspects of imagery (in particular, spatial precision) has been associated (negatively) with V1 surface area (Bergmann et al., 2016).

Because there is evidence that congenital and early-onset low vision may result in permanent and irreversible changes in cortical wiring and structure, while late-onset is less likely to produce such changes (Legge & Chung, 2016), we sought to examine possible differences in imagery responses among those groups, as well as those with restricted visual fields.

Materials and methods

Subjects

Our 41 participants were adults, categorized into four groups: *Normally sighted; early low vision* (Snellen acuity 0.4 logMAR or worse and onset of low vision prior to age 18); *late low vision* (Snellen acuity 0.4 logMAR or worse and onset of low vision at or after age 18); and *restricted visual fields* (spanning less than 20° of visual angle). There were 10 participants in each group, except the late low vision group, which had 11 participants. Participant characteristics are shown in Table 1. All subjects provided informed consent. The procedures of this study were approved by the University of Minnesota Institutional Review Board.

Procedure

We analysed imagery responses of our participants through a questionnaire, which was conducted by telephone for most participants. Before the telephone call, each participant was first sent by postal mail, a visual acuity test with which we were able to ascertain and confirm their reported visual acuity, without requiring a lab visit. The call began with several questions surveying the history of their vision status and their prior experiences with visual mental imagery. Subsequently they were administered the visual acuity test, followed by an abbreviated imagery vividness questionnaire based on Marks (1973), and a questionnaire in which they were asked to form mental images of 10 objects, and answer

Table 1. Characteristics of the participant sample

Vision group	*N*	Gender	Age	Age at onset of low vision	Visual acuity (logMAR)
Normal	10	M: 4 F: 6	Range: 19–64 Median: 30	N/A	0
Early low vision	10	M: 4 F: 6	Range: 25-62 Median: 37	Range: 0–14 Median: 0	Range: 0.66–1.74 Mean: 1.13
Late low vision	11	M: 1 F: 10	Range: 47–77 Median: 66	Range: 23–70 Median: 58	Range: 0.4–1.48 Mean: 0.99
Restricted field	10	M: 4 F: 6	Range: 25–68 Median: 57	Range: 0–58 Median: 30.75	Range: 0.16–1.36 Mean: 0.65

Note. Normally sighted subjects were assigned an acuity of 0 logMAR based on their measured visual acuity of 20/29 or better and self-reported normal vision questions about their imagery. This questionnaire provided the bulk of the data reported here.

Remote visual acuity test

The visual acuity test was modelled after the Early Treatment Diabetic Retinopathy visual acuity chart (Ferris, Kassoff, Bresnick, & Bailey, 1982). It was printed on white paper and contained the same letter sequence as Chart 1 of that test, using the same Sloan optotypes as used in the original chart. It was provided to participants in a folder that could be folded back to form a table-mounted stand that could sit on a table, with the chart, which was printed in landscape orientation, in a comfortable viewing position. One inside pocket of the standing folder contained a practice acuity test; the other the actual test, so that by rotating the folder the participant could choose either the practice or the real test. The folder was also equipped with a cord strung with two beads marking two viewing distances, 20 and 40 cm. We express acuities using the common log minimum angle of resolution (logMAR) scale. Considering both viewing distances, the full range of acuities that could be assessed in this manner was logMAR 0.16 (20/29) to 1.86 (20/1447). Participants were encouraged to take the test in a well-lit room like a kitchen, with overhead lighting, and without glare sources in their field of view. After taking the practice test, the full test was administered. Testing stopped when the participant erred on three or more letters (of five) on a line. The logMAR score gave credit for correct items within the line terminating the test (i.e., letter-by-letter scoring).

Visual Vividness of Imagery Questionnaire subset

The Visual Vividness of Imagery Questionnaire (VVIQ; Marks, 1973) prompts for ratings on a 5-point scale, of the vividness of imagery of specific items and features. It has been claimed that imagery vividness, as measured by the questionnaire, is strongly associated with performance on a wide range of perceptual-motor and cognitive tasks (Marks, 1999). We used a four-item subset, asking our subjects to rate (with 1 denoting perfect clarity as if seeing the item, 5 denoting no image at all, and 2–4 denoting intermediate levels of vividness). The items were:

1. The sun is rising above the horizon into a hazy sky.
2. The sky clears and surrounds the sun with blueness.
3. Clouds. A storm blows up, with flashes of lightning.
4. A rainbow appears.

Imagery questionnaire

The imagery questionnaire asked participants to form mental images of a set of 10 items and then to answer questions about each of those images. The items were selected to span a wide range of sizes and to be familiar to potential subjects. The order of the images was fixed, in the same single pseudo-random order for all conditions described below. The items (in their fixed order) were a stop sign, a dinner fork, a school bus, a wall clock ('that you might find in an office or classroom'), an aspirin pill, a guitar, a classic farm house, a zebra, a one-foot desk ruler, and an upright piano. For purposes of our analysis we also measured (where possible) or estimated the 'ground truth' sizes of the items. These are shown in Table 2.

Table 2. Ground truth sizes of the items used in the imagery questionnaire, in feet

Aspirin pill	Dinner fork	Wall clock	Desk ruler	Stop sign	Guitar	Upright piano	Zebra	School bus	House
0.02	0.67	1	1	2.5	3.17	5	7.25	35	60

We also examined reported ability of our participants to resolve in their imagery certain critical features of the imaged objects. There were no feature dimensions that we were able to sensibly estimate for two items (farm house and zebra). Zebra stripe separation would seem to be a good candidate, but zebra stripe width varies widely depending on species (as well as within a single animal); distance between windows, which might seem a reasonable feature to use for the farm house, also varies widely depending on house design and we could find no standard or consistent estimate). We refer to the remaining eight items as the *reduced item set*. Table 4 shows the 'ground truth' distances at which a normally sighted observer (with visual acuity of logMAR 0.0) can resolve the features in this reduced set.

Data analysis

Our data for some modelling analyses were unbalanced due to the eleventh late-onset low vision participant and due to response omissions or ambiguities on some items, so we used the modelling package lme4 (Bates, Mächler, Bolker, & Walker, 2015) which does not require equal group sizes, and which runs in the statistical language *R* (R Core Team, 2014). *p*-Values for fixed effects were obtained from Type II Wald χ^2 tests using the car R package (Fox & Weisberg, 2011). To assess differences between participant groups, we used either the R emmeans package (Lenth, 2019), with degrees of freedom computed using the Kenward–Roger method, or the R multcomp package (Hothorn, Bretz, & Westfall, 2008). Imaged distances were log transformed due to their large range. There were a few scattered zero imaged distance responses: where that was the case 1 was added to all imaged distances before log transformation, to allow statistical analyses on log transformed distances.

Results

Imagery vividness

We looked at the self-reported vividness of our subjects' imagery as measured by a subset of the VVIQ, to see if there were any systematic differences among groups. There was no significant main effect of vision group, nor was there a significant correlation between visual acuity and imagery vividness.

Object distance in free imagery

A key finding in support of the depictive nature of visual imagery is that objects imaged by a sighted person are spontaneously imaged at distances that are monotonically related to their size, suggesting that their representations are vision-based (Kosslyn, 1978). This is in contrast to findings with congenitally blind persons (who by definition have never experienced vision), who report imagery that is dissociated from vision and thus whose distance-size relationship is not strictly monotonic and instead suggests a tactile or haptic representation (Arditi et al., 1988). A first goal of our study was to replicate the Kosslyn (1978) finding with normally sighted subjects, and if so, to see if the same relationship holds in subjects with our three categories of low vision. In our questionnaire, for each item we asked participants to image the object and to describe any details about the imaged objects that they are able to. The purpose of the descriptions was both to ensure that detailed images were formed. After describing each item, participants then were asked to provide the distance of the object in their imagery, in whatever units they were comfortable with. The results are shown in Figure 1.

We found the following simple model of this relationship containing only the parameter of object size alone (and ignoring all visual performance and vision group variables) to be a reasonably good predictor (χ^2 (1) = 300.2, $p < 2.96e\text{-}67$) of spontaneously imaged object distance:

$$\log D_f = 0.733 + 0.331 \log S + \varepsilon \quad (1)$$

where $\log D_f$ is the base 10 logarithm of free imaged distance, and S is object size. The standard deviation about the intercept reflecting individual subject variability was 0.1665. The slope falls between 0.293 and 0.368 with 95% confidence.

The relationship between object size and imaged distance is qualitatively consistent with earlier findings of Kosslyn (1978) and Arditi et al. (1988) using sighted subjects in that it found imaged distance to be monotonically related to object size. But the model in Equation 1, which expresses both size and distance as logarithms, is linear with a slope of

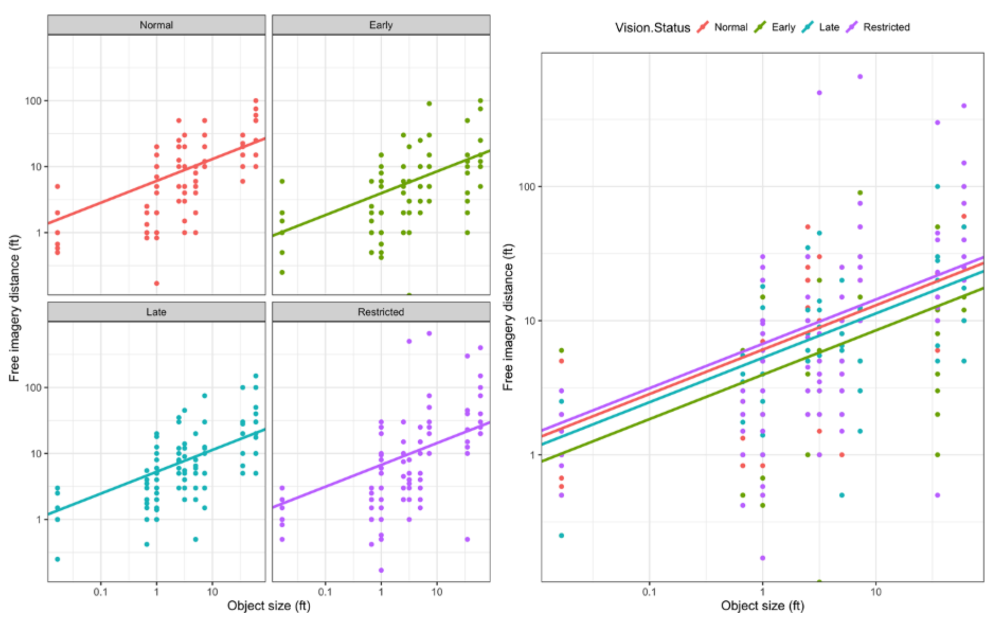

Figure 1. Imaged distance versus size, for each of the four vision groups. Object sizes are from Table 2. The left side shows plots for the four vision groups. The right side shows the same data in a single graph, with data from each group shown in a different colour. Lines are fits to a mixed effects model with log size and vision group as fixed effects and participants as a random effect.

approximately 0.3 (for all vision groups), and implies a power law with the exponent equal to the slope. It indicates that the growth of free imaged distance with increasing object size is greatest for small objects (which are generally viewed in real life at a close distance), whereas larger objects are freely imaged at distances that grow far less with increasing size. The slope of 0.3 suggests that this is a highly compressive relationship.

The Pearson correlation coefficients between imagery distance and object size, over all subjects and broken down by vision group are shown in Table 3. The correlation coefficient of 0.617 for all subjects is highly significantly different from zero ($p < 2.2e\text{-}16$). The group *r*'s, however, are not significantly different from one another, consistent with the spread of imaged distances being similar for all groups.

Does vision group have an impact on imaged distances? The right side of Figure 1 suggests that those whose vision declined early in life (i.e., the early low vision group) tend to image objects at closer distances than any of the other vision groups, so we examined the impact of adding vision group to the simple model of Equation 1 with a term added for that variable.

Vision group did show a significant effect ($\chi^2(3) = 8.324, p < .040$), and a comparison of this model with the simpler one of Equation 1 showed it to be a significantly better fit to the data ($\chi^2(3) = 8.3197, p < .040$), showing at the very least an impact of low vision on distance at which visual objects are spontaneously imaged. Slopes were not significantly different among the four vision groups.

The smaller imaged distances of the early low vision group shown in Figure 1 suggests that those who have had low vision from a younger age may have imagery that is offset towards the closer distances at which they likely recognize common objects in their experience. We quickly realized that this may be due to those with early low vision having lower visual acuity. And in our participant sample, logMAR visual acuity did differ significantly among the three low vision groups ($\chi^2(2) = 106.4$, $p < 7.683e\text{-}24$). Since those with early low vision had on average lower visual acuity than those with late or restricted field low vision, we decided to examine visual acuity as an alternate, more compact predictor of imaged distance.

As expected, a model of imagery distances that incorporates the possible influence of visual acuity, like vision group, also shows logMAR to be a significant predictor of the imaged distances ($\chi^2(1) = 3.996, p < .0456$). When the model incorporating vision group is compared to the one incorporating visual acuity, neither is a significantly better fit to our data. Since visual acuity is an inherently simpler variable than vision group (which we defined with relatively arbitrary age boundaries), we add the acuity variable to the simple model of Equation 1:

$$\log D_f = 0.883 + 0.323 \log S - 0.177A \tag{2}$$

where D_f is free imaged distance, S is object size and A is logMAR acuity. Below we report additional situations where acuity predicts other aspects of low vision imagery.

Table 3. Pearson correlation between log free imaged distance and log object size for the vision groups separately and aggregated

Normal	Early	Late	Restricted	All
0.694	0.574	0.654	0.601	0.617

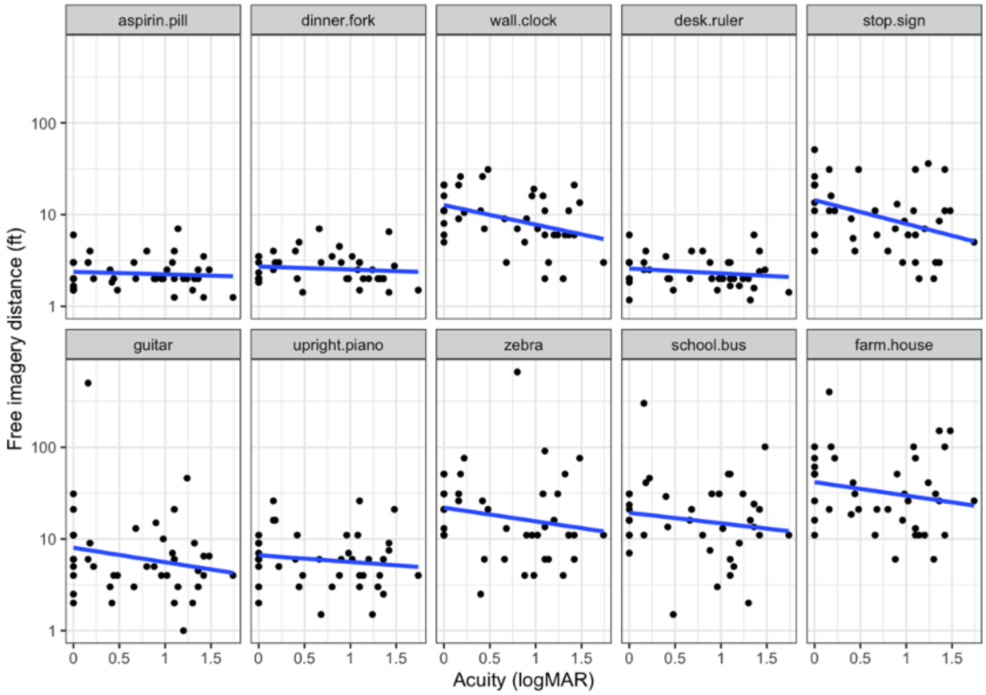

Figure 2. Imaged distance against logMAR for each item. The rise of the data points from small items to large items reflects the effect of object size on free imagery distance (shown explicitly in Figure 1), while the decline of imagery distance with increasing logMAR within each item panel reflects the effect of reduced acuity.

We also examined whether years of low vision predicts the imaged distances. It does not, nor was it significantly correlated with logMAR acuity in our sample. Thus, while we found a significant difference between vision groups in predicting imaged distances over the full range of object sizes, logMAR acuity appears to underlie this difference.

Turning now to the relationship between logMAR acuity and free imagery distance separately for each object (Figure 2), we see significant effects on the log of free imagery distance of both logMAR acuity (within each subplot; χ^2 (1) = 4.9366, $p < .026$), and of individual item (between subplots; χ^2 (1) = 329.696, $p < 2e\text{-}16$). But while the slopes of the fits in the subplots appear different in the figure, which would indicate an interaction between logMAR acuity and the log of item size, there was in fact no significant interaction, so there is no evidence that reduced acuity impacts imagery of different objects differently. The main empirical result here, then, is that imagery distances are shorter for people with poorer acuity.

As an aside, it is interesting to note that the wall clock and the desk ruler have the same ground truth size of 1 ft, but the distance at which the wall clock is imaged is substantially greater than that of the ruler. We believe that this may be due to the fact that a wall clock is generally viewed at a distance, while a desk ruler is ordinarily used at arm's length. We believe that this kind of difference in function among objects can have a strong impact on the distance at which they are imaged. Indeed, the functional significance of objects we view in real life might be one source of the compressive relationship between free imagery distance and object size. For some visual objects, there could also be something like canonical visual distances at which objects are typically viewed and hence tend to be imaged, analogous to Konkle and Oliva's (2011) notion of canonical visual size. Large objects tend to be viewed at greater distance than small objects, and when they are viewed at closer distances only parts of the object may be visible.

Object 'overflow' distances

We also examined the distance at which our participants reported that objects in visual imagery 'just filled' their 'imagery field', a technique pioneered by Kosslyn (1978) and subsequently used by Arditi et al. (1988) and Vanlierde and Wanet-Defalque (2005). In our questionnaire, we instructed subjects to imagine that they were walking towards or away from the objects, and to 'find the point at which the whole object just fits into your imagery field of view, and then estimate the distance in feet'. Objects imaged as they were in the free imagery condition (i.e., without these instructions), might be expected to be imaged at greater distance than objects imaged at the 'just filling but not overflowing the imagery field' distance, and this is exactly what we found.

Figure 3 shows the ratio of free imagery to overflow imagery distance for the 10 items, for the four vision status groups. There is substantial variability between items as well as between groups, but for nearly all groups and items, the ratio is much greater than 1. Since objects are freely imaged on average at a substantially greater distance than that which can just accommodate the imaged size at overflow, it is clear that that visual imagery mirrors ordinary visual perception in depicting objects within a field of quite limited extent. This is true for all low vision groups, as well as for the normal group. We had anticipated that people with narrow visual fields would exhibit smaller ratios if their imagery field was also narrower than normal. If so, the overflow imagery distance should be greater than for normally sighted subjects, resulting in a lower ratio. This was not the case; if anything, the

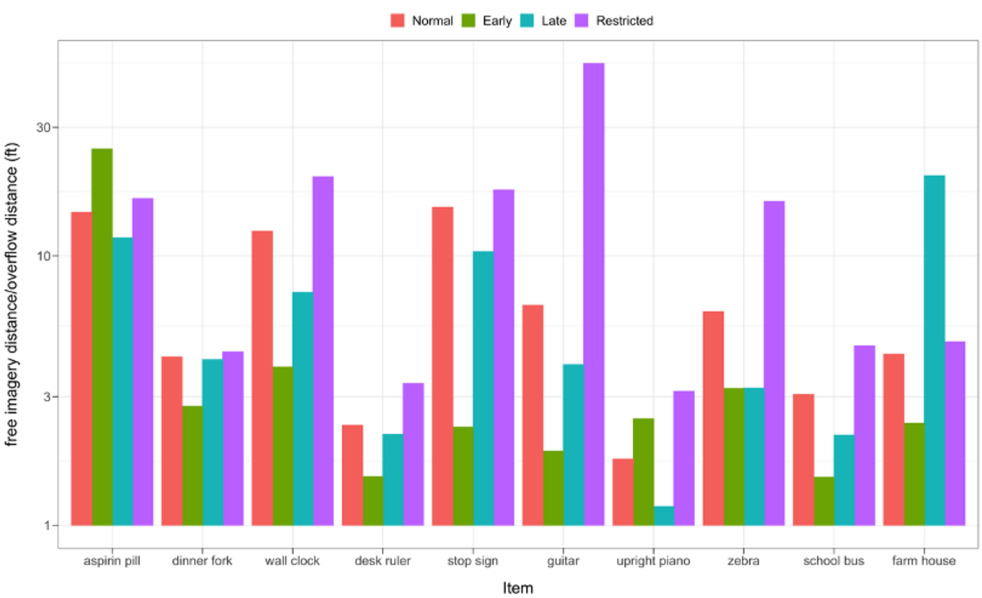

Figure 3. The ratio of imaged overflow distance to free imagery distance, for each item.

restricted-field group had higher ratios than the other groups (though not significantly higher). Despite this, the results from the overflow condition do generally support the idea that everyone with low vision, irrespective of how long they have lived with low vision, continue to experience imagery in very much the same way, acuity-adjusted, as those with normal vision.

Feature resolution in imagery

In this part of the questionnaire, we asked participants to identify the farthest distance at which in their images they could just make out key features of the objects. As two examples, for the upright piano, we asked them to identify the distance where in their imagery they could just distinguish the individual black keys; for the aspirin pill, the distance at which they could read the letters or numbers on the pill. Again, as with the overflow condition, we asked them to mentally move closer to or farther away from each object until 'you can just barely make out the details' of the feature we asked about. Since 'critical' features of large objects tend to be larger than those of small objects, we should expect a similar linear dependence of the log of this resolution distance on log object size based on our free imagery results, and this is just what we found. Normally sighted subjects reported imaging the critical features at greater distance than those in each of the low vision groups (Early Low Vision ($t(36.9) = 5.656$, $p < .0001$) , Late Low Vision ($t(36.7) = 4.020$, $p < .0015$) and Restricted Fields ($t(37) = 2.971$, $p < .0256$) groups. But none of the low vision groups differed significantly from one another. As with free imagery, logMAR visual acuity was also an excellent predictor ($\chi^2(1, N = 320) = 7.166$, $p = .00743$) of feature resolution distance.

Imaged feature resolution versus perceptual feature resolution

How well do those with low vision resolve small object features in their imagery relative to how they resolve them in real life with their visual perception? We addressed this question with all our participants. For this purpose our normal subjects were assumed to have acuity of 0 logMAR (Snellen 20/20), As above, we used as ground truth, estimates of actual resolution distance for a person with logMAR of 0.0 (see Table 4), and for the low vision subjects, scaled those values appropriately based on their measured visual acuity.

We refer to these distances, which reflect the distance at which an observer should be able to resolve a feature, as 'perceptual resolution distance'. Figure 4 plots the ratio of participants' imagery resolution distance to perceptual resolution distance for the reduced item set for both normal observers and those with low vision. Most of the ratios are less than 1 for both normal and low vision subjects, reflecting a tendency to behave in imagery as if we have worse acuity than our measured acuity. The low vision subjects had substantially more variable ratios than the normal subjects for nearly all items, but the overall median ratio for low vision subjects was somewhat higher (0.37), than that of the normally sighted subjects (0.28; $Z = 2.0656$, $p = .039$).

Both the reduction in acuity in imagery of both normally sighted and low vision subjects and the fact that it scales with perceptual visual acuity are effects that have been reported earlier. Finke and Kosslyn (1980) found peripheral visual two dot discrimination judgments to scale similarly in perception and imagery for their normally sighted subjects, and found acuity in imagery to be lower than in perception. In addition, they found this reduction to be especially high in those whose imagery was less vivid.

Table 4. Estimated distances in feet for a person with 20/20 to resolve key critical features on items

Item	Aspirin pill	Desk ruler	Dinner fork	Wall clock	Guitar	Piano	Stop sign	School bus
Normal Visual resolution distance (ft)	7.1	7.1	35.8	86	114	143	344	748
Feature used	Letter height/5	Number height/5	Tine separation	Number height/5	String spacing	Black key spacing	Letter height/5	Letter height/5
Feature size (in)	0.025	0.025	0.125	0.3	0.4	0.5	1.2	2.4

Note. Features are pill: read 1/8 inch etched letters; ruler: read 1/8 inch numbers; fork: distance between tines; clock: read 1.5 inch numbers; guitar: resolve 0.4 inch separation between strings; piano: resolve individual black key; stop sign: read 6 inch upper case letters; bus: read 12 inch upper case letters on front of bus.

Discussion

Our findings support the view that imagery in low vision is influenced by visual perception, particularly visual acuity. They thus support a depictive interpretation of imagery, consistent with a contemporary consensus favouring this view (Pearson & Kosslyn, 2015). Specifically, we have quantitative evidence that the imagery of those with low vision is strongly influenced by their closer viewing of recognized objects and reduced visual acuity (Figures 1 and 2), and evidence that there is an 'imagery field' of finite extent that can be made to perceptually contain imaged objects, that operates similarly in normal and low vision (Figure 3). But we did not design our study with the intent of distinguishing among theories and recognize that our findings are not decisive concerning theoretical interpretations with respect to the decades-long imagery debate.

To replicate the Kosslyn (1978) result, as well as the normal vision data in the Arditi et al. (1988) and the Vanlierde and Wanet-Defalque (2005) papers, our data should show imaged distance to be monotonically related to the size of the object being imaged. The underlying theory, of course, is that we place objects in our imagery at distances that are influenced by their angular sizes. Our subjects do show an increase in free imagery distance with object size, in support of that idea. Note that our results, like the earlier studies of Arditi et al. (1988) and Vanlierde and Wanet-Defalque (2005), as well as those of Kosslyn (1978, 1980) find only a loose correspondence between inferred angular sizes and imagery distances that is characterized in our study by the highly compressive relationship between object size and imaged distance. This finding is roughly consistent with early studies of size and apparent distance (Foley, 1980; Gilinsky, 1951), with other studies of size and imaged distance (Hubbard & Baird, 1988; Hubbard, Kall, & Baird, 1989), and with the recently articulated notion of canonical visual size (Konkle & Oliva, 2011). In the Konkle and Oliva study, (canonical) visual size was found to be proportional to the logarithm of size assumed by an observer in tasks of drawing and preferential viewing as well as imagery. All of these studies find some kind of compressive relationship between size and apparent or imaged distance.

We also found some influence of the typical ways people interact with objects, especially in the difference in imagery between the desk ruler and wall clock items (see especially Figures 3 and 4) that is less supportive of a depictive view of imagery. Because people tend to interact with desk rulers at a closer distance than wall clocks, those interactions may bias the distances at which the objects are imaged. Thus, perhaps a canonical interaction distance sometimes competes with a tendency to portray objects of equal linear size at the equal-angular distances.

Interestingly, we found that both normally sighted people and those with low vision report lower resolution in their imagery than would be expected from estimates of their visual acuity in real life (see Figure 4, left panel). The subjects with low vision had resolution distances in their imagery that were slightly higher relative to their acuity than those of the normally sighted subjects. We can speculate that this is because in everyday experience, those with low vision are usually functioning closer to their acuity limit than those with normal vision. Their imagery may mirror a similar reduced acuity reserve that is observed in reading performance (Legge & Bigelow, 2011; Whittaker & Lovie-Kitchin, 1993). There is also considerable evidence, from magnetic resonance imaging, that early developmental, congenital, and long-standing eye disorders associated with reduced visual acuity (including nystagmus, amblyopia , glaucoma, and age-related macular degeneration, are themselves associated with structural occipital and in some cases, frontal lobe changes (Prins, Hanekamp, & Cornelissen, 2016). Since these structures form

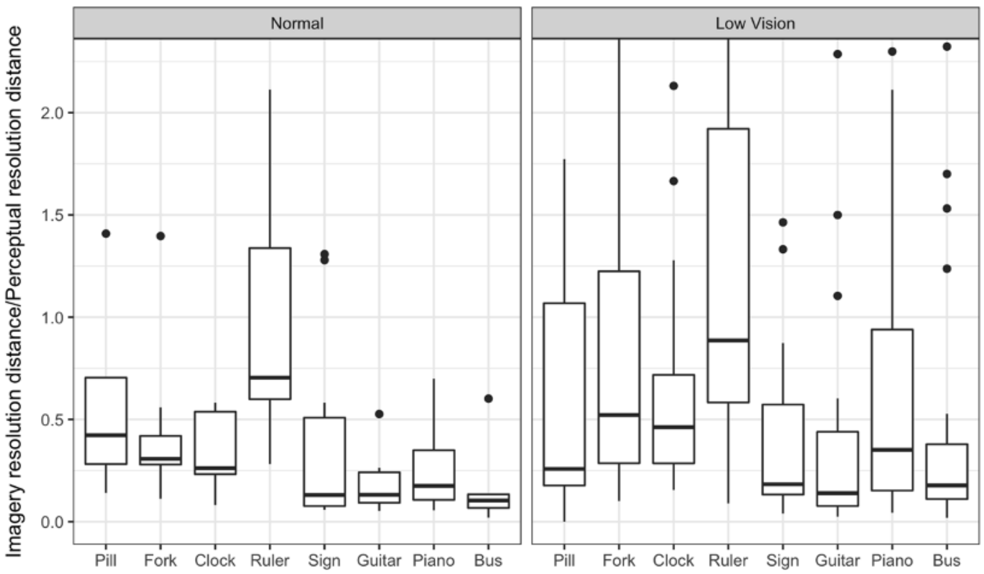

Figure 4. Ratio of subject-estimated resolution distance to perceptual resolution distance) for our 10 normally sighted participants (left) and our 31 low vision participants (right). The box hinges indicate the interquartile limits, with the median indicated within. The whiskers indicate values departing from the hinges by no more than 1.5 times the interquartile range. The remaining points are outliers.

the likely substrate for visual imagery (Pearson & Kosslyn, 2015), our results suggest imagery as an additional correlate.

Does the prior literature suggest a canonical or 'natural' angular image size? Kosslyn (1978) found inferred angular imagery field sizes in normally sighted participants to vary between 13 and 50°, a rather large range. He also reported that inferred angle was dependent on prior instructions. For example, instructing subjects to use an imaged desk ruler to 'measure' the overflowed imagery, yielded larger estimated field extents. Furthermore, in his study, some items (specifically large and small animals) were not consistent with a linear increase of visual size with distance. Kosslyn also points out that images often don't have borders or well-defined edges, leading to more uncertainty in overflow distance estimates. So, while there appears to be no fixed canonical angular image size, substantial variation in observed sizes may be due to object type, typical usage, subject instructions, and other factors. Generally, though, our findings are consistent with the idea that retinal size plays some role in determining imaged size, in that large objects are naturally and spontaneously placed at greater distances and overflow at greater distances than small objects.

An important caveat is that our study uses a modest sample size of low vision pathologies with a broad range of severity. Because of this, and because even the imagery studies using normally sighted subjects show wide variability (including the seminal Kosslyn, 1978 study cited above), the variability in our data is perhaps not surprising. Unfortunately, the small size and high variability of our sample make us wary of accepting null effects we observed in the study.

A final message to take away from the results we have obtained is one that accords with the large body of literature on low vision that has accrued over the last seven decades since pioneers Eleanor Faye, Gerald Fonda, and George Hellinger first championed the use of residual vision (Goodrich & Bailey, 2000) over the sight-saving philosophy that guided vision rehabilitation prior to that: Vision forms the perceptual basis of visual mental imagery for those who have low vision, in a manner that is qualitatively similar to that of those with normal vision, after adjusting for reductions in visual acuity. It is therefore very likely that those with partial vision loss employ imagery in cognition, including problem-solving, in very much the same way as those with normal sight.

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Conflicts of interest

All authors declare no conflict of interest.

Author contributions

Aries Arditi (Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing) Gordon Legge (Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Writing – original draft; Writing – review & editing) Christina Granquist (Data curation; Investigation; Writing – review & editing) Rachel Gage (Data curation; Investigation) Dawn Clark (Methodology)

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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