Estimating the Amount of Mental Effort Required for Independent Mobility: Persons with Glaucoma

Duane R. Geruschat[1,2] *and Kathleen A. Turano*[1]

Purpose. To validate the use of the secondary-task method to estimate the amount of mental effort required for independent travel and to determine how the amount of mental effort varies with characteristics of the environment.

Methods. Reaction time (RT) to a secondary task (randomly presented vibrations) was obtained in 28 persons with glaucoma as they walked in four different environments: hallway, high-pedestrian area, approach-to-stairs area, and stairs. Cronbach's α was used to assess the reliability of the secondary-task RT measures from the split-half measures of the high-pedestrian area. The construct validity of the RT measures as an estimate of mental effort was assessed by (1) the association between the RT scores and the item measure scores for similar environments derived from a Rasch analysis of perceived difficulty ratings obtained in a separate group of 83 persons with glaucoma and (2) the association between the RT scores and the severity of visual field loss.

Results. Reliability was supported by a Cronbach's α coefficient of 0.89. Construct validity was also supported by the data: (1) Log RT scores were linearly related to the Rasch analysis item measures for comparable mobility situations ($P = 0.008$), and (2) the log RT, averaged across the four environments, was linearly related to the mean deviation score of the Humphrey Visual Field Analyzer (estimate of visual field loss; $P = 0.003$; Carl Zeiss Meditec, Inc., Dublin, CA). A comparison of the log RT scores obtained in the four environments showed significantly higher log RT scores in the stairs area than in the high-pedestrian and hallway environments, whereas the log RT scores in the high-pedestrian and hallway environments were not significantly different.

Conclusions. The findings in this study demonstrate the reliability and construct validity of the secondary-task RT measure as an estimate of the amount of mental effort required to travel independently. It is sensitive to environmental characteristics and the loss in a walker's visual field. The method could be an objective way to document those who may benefit from professional intervention and to evaluate the effectiveness of an intervention. (*Invest Ophthalmol Vis Sci.* 2007;48:3988–3994) DOI:10.1167/iovs.06-1193

Loss of the peripheral visual field increases the perceived difficulty of independent travel,[1–5] with the degree of difficulty varying depending on the characteristics of the environment. Persons with glaucoma or retinitis pigmentosa (RP) report little to no difficulty walking in areas that are familiar, walled (as in hallways), or contain waist- and shoulder-height objects. However, walking in areas that are dark, have descending stairways, or are crowded is perceived as difficult.[2,3]

Although self-reported measures of perceived difficulty are useful in that they may actually be more closely related to decisions about independent travel than are traditional performance measures, objective measures have the advantage of allowing for a direct comparison across groups, training, and environmental situations. Walking speed or variations of walking speed is the most common outcome measure for quantifying difficulty of independent travel.[6–8] However, walking speed is not an ideal estimator of travel difficulty, because it varies broadly across individuals and environmental situations, such as in turning corners or walking stairs, due to changes in body mechanics. Decreased walking speed to increase environmental preview and increased walking speed to increase safety when crossing the street challenge the popular notion that faster walking indicates superior travel skills. Other popular outcome measures of travel difficulty (e.g., the number of unwanted contacts or orientation errors)[9–13] also fall short of the ideal outcome measure, in that they are relatively rare events, requiring an extensive number of trials because of floor effects. Moreover, in the subjects whose mobility is severely impaired, their performance is so unsafe that they sometimes withdraw from a lengthy test before its completion.

One strategy that shows promise in its ability to quantify difficulty in independent travel is based on secondary-task methodology, whereby reaction time (RT) to a secondary task is measured and used to estimate the amount of mental effort required for performing the primary task. The secondary-task method requires one to maintain performance on the primary task (in our case, walking) while completing a secondary task. In this model, changes in performance on the secondary task reflect the mental effort necessary to maintain performance on the primary task. The paradigm is based on the assumption that mental operations draw from a limited-capacity central mechanism and that interference between a primary and a secondary task can assess the extent to which the primary task makes processing demands on the limited central system.[14]

Shingledecker[15] was the first to introduce the secondary-task methodology to blind mobility research. He measured RT to a wrist-applied vibration in three sighted, blindfolded men who walked with a long cane in each of three outdoor routes. The routes varied in complexity, from a simple obstacle-free straight pathway to a busy shopping district, which consisted of three road crossings, seven decision points, high-pedestrian traffic, and obstacles located at unpredictable positions. The primary task was to travel safely and efficiently, and the secondary task was to respond quickly to the randomly presented vibrations. The study showed that RT to the vibrations increased with route complexity. However, the difference in environmental complexity was so extreme in this study, comparing the RT while walking an obstacle-free path with that while walking in a busy shopping district, that it is unclear whether the method is sensitive enough to detect differences in mental effort for more subtle environmental changes.

From the [1]Wilmer Eye Institute, The Johns Hopkins University School of Medicine, Baltimore, Maryland; and the [2]Maryland School for the Blind, Baltimore, Maryland.

Supported by a grant from the NIH/National Eye Institute EY07839 (KAT).

Submitted for publication October 5, 2006; revised March 29 and May 18, 2007; accepted June 22, 2007.

Disclosure: **D.R. Geruschat**, None; **K.A. Turano**, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Kathleen A. Turano, Wilmer Eye Institute, Lions Vision Center, 550 North Broadway, 6th Floor, Baltimore, MD 21205; kturano@jhmi.edu.

Table 1. Descriptive Statistics of the Subjects' Visual Function Measures

	Max.	Min.	Mean	SD
Log MAR (Snellen equivalent)	−0.18 (20/13)	0.66 (20/91)	0.10 (20/25)	0.20 (20/32)
Log CS	1.85	0.9	1.53	0.22
MD (better eye)	0.96	−26.69	−9.91	8.84
MD (worse eye)	−0.58	−30.00	−15.60	9.43
CPSD (better eye)	1.31	11.85	6.30	3.23
CPSD (worse eye)	1.59	15.71	9.47	3.62

Some evidence suggests that the method may be sensitive to more subtle differences in mental effort. Using a secondary-task method, we[16] showed poorer secondary task performance (RT to auditory beeps) in a group of 15 persons visually impaired by RP compared with a normally sighted control group of 17 persons, when the primary task was walking an indoor circuitous route with obstacles but not when the primary task was walking an obstacle-free hallway.[16]

In this study, we assessed the reliability and construct validity of the secondary-task RT measures as an estimate of the amount of mental effort required for independent travel. Reaction time to randomly presented vibrations was obtained in persons with glaucoma as they walked in four different environments: hallway, high-pedestrian area, approach-to-stairs area, and stairs.

METHODS

Subjects

Twenty-eight subjects (15 men) with diagnosed open-angle glaucoma participated in the study. The ages of the subjects ranged from 25.0 to 84.3 years (mean, 64.0; SD, 16.3). The subjects had a complete ophthalmic examination by a glaucoma specialist on the day of testing. Those with glaucoma with apparent nonglaucomatous retinal disease or other ocular disease were excluded from the study. Any subject with musculoskeletal limitations (e.g., orthopedic), diabetes, or endurance limitations (e.g., coronary problems) was excluded from participation. Informed consent was obtained from each subject after the nature and possible consequences of the study were described. The research adhered to the tenets of the Declaration of Helsinki and was approved by the Johns Hopkins Medical Institution's committee on human experimentation.

Visual Function Tests

Measures of vision function included visual acuity, contrast sensitivity, and visual fields. Visual acuity was measured binocularly at a viewing distance of 3 m with an ETDRS (Early Treatment of Diabetic Retinopathy Study; Lighthouse International, New York, NY) acuity chart[17] transilluminated at approximately 100 cd/m^2. The number of letters correctly read was converted to the logarithm of the minimum angle of resolution (logMAR) based on the methods of Bailey et al.[18] Peak contrast sensitivity was measured binocularly at a viewing distance of 1 m, with the Pelli-Robson chart[19] with overhead illumination of 85 cd/m^2. Visual fields were measured monocularly with the 24-2 threshold program of the Humphrey Visual Field Analyzer (Carl Zeiss Meditec, Inc., Dublin, CA). This program tests 54 points within the central 24°. Two visual field parameters were extracted from the program, the mean deviation (MD) and the corrected pattern SD (CPSD). Age did not correlate significantly with any of the visual field parameters ($r < 0.21$ for all). The visual functions of the 28 subjects with glaucoma spanned a wide range and are reported in Table 1.

Secondary Task

The secondary task was to respond as quickly as possible to vibrations that were randomly emitted from a handheld joystick with the handle modified to house a vibrating device. Subjects were to respond when they first felt the vibration, by squeezing the index-finger trigger of the joystick, which they were holding in the nondominant hand. The timing of the vibrations was controlled by a computer program on a handheld computer (200LX Palmtop; Hewlett Packard, Palo Alto, CA). The 120-Hz vibrations were 100 ms in duration, and their onset occurred anywhere from 1 to 2 seconds after the previous response.

Mobility Route

The course was an 87.9-m indoor route that consisted of four segments that varied in environmental characteristics: a 21.1-m hallway that was obstacle and pedestrian free (hallway); a 8.35-m, pedestrian-free area immediately adjacent to a descending stairway (approach-to-stairs); a 14.9-m descending stairway (stairs); and a 29.4-m open area with a high number of pedestrians (mean $n = 15.6$; SD, 5.5; high-pedestrian). The high-pedestrian area was a wide corridor within the Outpatient Center at the Johns Hopkins Hospital, and the pedestrians, who were mainly adults, were moving both in the direction of, and opposite to, the direction in which the study participants were moving. The four segments had natural boundaries and, as such, varied in distance, travel time, and number of samples.

Procedure

The experiment began with instructions given to the subject about how to hold the joystick and how to respond to the vibrations. The subject practiced responding to the vibrations until he or she felt comfortable using the device. A baseline RT was measured while the subject stood for 30 seconds and responded to the vibration. Two baseline RT estimates were obtained, one at the beginning and one at the end of the mobility route, so that time effects (practice or fatigue) could be detected. Because the secondary task method requires that performance on the primary task remain constant with the introduction of the secondary task, a baseline measure of the primary task performance (i.e., walking speed), was needed. Therefore, the subjects walked the mobility route twice, once while responding as quickly as possible to the vibrations and another time, without the vibrating device. They were instructed to walk at their normal pace for both passes on the route. Every other subject performed the secondary task on the first pass, and the other subjects performed the secondary task on the second pass. At the beginning of each route segment, directions were provided in short descriptions. The first and last segments were the hallway. This segment was repeated, and the RT scores from the two samples were averaged to form a composite hallway score, to minimize any effect due to the passage of time. The next segment to be experienced was the approach-to-stairs, followed by stairs, and finally the high-pedestrian area.

Data Analysis

The outcome of interest was the RT to the secondary task. The average RT was calculated for each subject and mobility segment. To reduce the heterogeneity of the variances of the RT scores in the various mobility segments, the scores were transformed by taking the natural logarithm of the average RT. Baseline RT was measured at the beginning and end of the mobility course, and the two measures were averaged to form the baseline RT, which was then used as a covariate

Table 2. Average Response Measures for the Baseline Condition and Each of the Four Mobility Segments

	Baseline	Hallway	Hi-Ped	Approach	Stairs
Samples (*n*)					
Min–max	9–15	5–13	5–14	1–6	4–19
Mean (median)	11.8 (12)	8.1 (8)	10.0 (10)	2.1 (2)	9.6 (8)
Time (s)					
Min–max	30.0–30.0	9.9–28.9	12.9–34.1	3.1–16.3	9.7–49.1
Mean (median)	30.0 (30.0)	19.0 (18.8)	24.5 (24.5)	5.7 (5.1)	24.2 (21.2)
RT (ms)					
Min–max	163.8–469.0	188.7–519.4	213.1–612.9	195.0–1000	193.7–707.8
Mean (median)	285.0 (265.9)	349.5 (347.9)	382.8 (361.6)	456.1 (398.5)	433.2 (395.6)

Hi-ped, high-pedestrian.

in the regression models, to account for natural individual differences in reaction time.

Reliability refers to the extent to which a measurement is consistent. One of the ways to test reliability is to assess the similarity in scores obtained from the same test administered in two or more testing sessions (test–retest reliability). The problem with this type of method is that scores may change over time because of practice or fatigue, if the sessions are spaced close together, or because of disease progression, if the sessions are far apart. One way to avoid the confounding effects associated with time is to assess the similarity in scores obtained in two halves of a single test (e.g., odd- versus even-numbered measures). We chose the split-half method and assessed the reliability of the secondary-task RT measures from the Cronbach's α coefficient. The split-half method entails calculating the score for each randomly divided half of the sample and determining the correlation between the two scores. Cronbach's α is equivalent to the average of all possible split half-correlations. We used the high-pedestrian segment to assess reliability of the secondary-task RT measure because this segment had the most samples (Table 2). Cronbach's α was computed with commercial software (Excel; Microsoft, Redmond, WA).

The approach-to-stairs had significantly fewer samples than did the other segments. Therefore, in all analyses that involved comparisons of the log RT scores across segments, the number of samples was used to weight the log RT scores.

Construct validity refers to the extent to which different methods that purportedly measure the same construct (or trait) yield similar results.[20] To assess the construct validity of the secondary-task RT measures as an estimate of mental effort, we performed two analyses. First, we performed a linear regression analysis on the log RT scores against estimates derived from perceived difficulty ratings for comparable mobility situations. We reasoned that if the amount of mental effort required for walking can be estimated from the RT to a secondary task, then we would expect that situations that have been reported to be difficult by persons with a similar diagnosis would have slower RT than situations that have been reported to be less difficult. The perceived difficulty measures were taken from a previously published study from a separate group of 83 patients with glaucoma who rated the difficulty of 35 mobility situations.[3] In that study, a Rasch analysis was performed on the subjects' ordinal difficulty ratings to derive interval measures of estimated visual ability (item measure). The item measure is specified in logit units and corresponds to the ability required for that particular mobility situation, with larger values indicating a greater ability required (more difficulty) for the situation.[2,3] Four mobility situations closely matched the predominant characteristic of the four mobility segments tested in the study. The item "avoiding bumping into walls" corresponds to the *hallway* segment and had an item measure (SE) of −0.92 (0.21). The item "bumping into people" corresponds to the *high-pedestrian* segment and had an item measure of −0.54 (0.19). The item "detecting descending stairwells" corresponds to the *approach-to-stairway* segment and had an item measure of 0.51 (0.16). The item "walking down steps" corresponds to the *stairs* segment and had an item measure of 0.49 (0.16).

Second, since self-reports of perceived difficulty correlate with degree of visual field loss, as indexed by the MD score of the Humphrey Visual Field Analyzer (Carl Zeiss Meditec, Inc.),[3] if the two measures are applied to the same construct, we would expect that the secondary-task RT would be associated with the MD score. To test the hypothesis that secondary-task RT increases with decreasing MD score, linear regression was performed on the log RT score as a function of the MD score of the Humphrey Visual Field Analyzer 24-2 test, adjusting for age, gender, and baseline RT.

To assess the associations between the log RT scores in each mobility segment and all measured vision variables, we used linear regression models and modeled log RT in two stages as a function of logMAR, peak log contrast sensitivity (CS), MD, and CPSD. First, we looked at the relationship of each variable to the log RT scores using univariate analyses to identify potential covariates, adjusting the vision variables for age, gender, and baseline RT. Next, we built a model with all the vision variables to determine which vision variables were associated with the log RT scores while adjusting for all other vision variables. Age and gender were included in the multiple linear regression model, despite nonsignificance in univariate analyses, to account for any variations in the vision variables related to these factors. Finally, two-way interaction terms were added to the multivariate linear regression model to determine whether their presence affected the findings of the simpler linear model.

The effect of environment on the amount of mental effort required for independent mobility was tested using a repeated-measures ANOVA of the log RT with mobility segment as the within-subjects factor. Log RT was weighted by the number of samples in each segment. To determine whether a main effect of environment occurs both in persons with early glaucoma and in those with advanced glaucoma, we identified the subjects with early and advanced glaucoma as those whose average MD scores were within the upper and lower quartiles, respectively. A mixed-design ANOVA was performed on the log RT scores with mobility segment as the within-subjects factor and subject group (early glaucoma, advanced glaucoma) as the between-subjects factor.

RESULTS

One of the assumptions underlying the secondary-task method for assessing the amount of mental effort required by the primary task is that performance on the primary task when performed in the presence of the secondary task is the same as when performed alone. To determine whether this assumption was satisfied in our study, we computed the percentage of change in walking speed for the two conditions (with and without the secondary task) over the entire course. For all but two subjects the percentage of change was less than 10%, a level we deemed reasonable considering the natural variability over the course (e.g., pedestrian flow). The two subjects whose walking speed changed by more than 10% were slower on the course when they had to perform the secondary task.

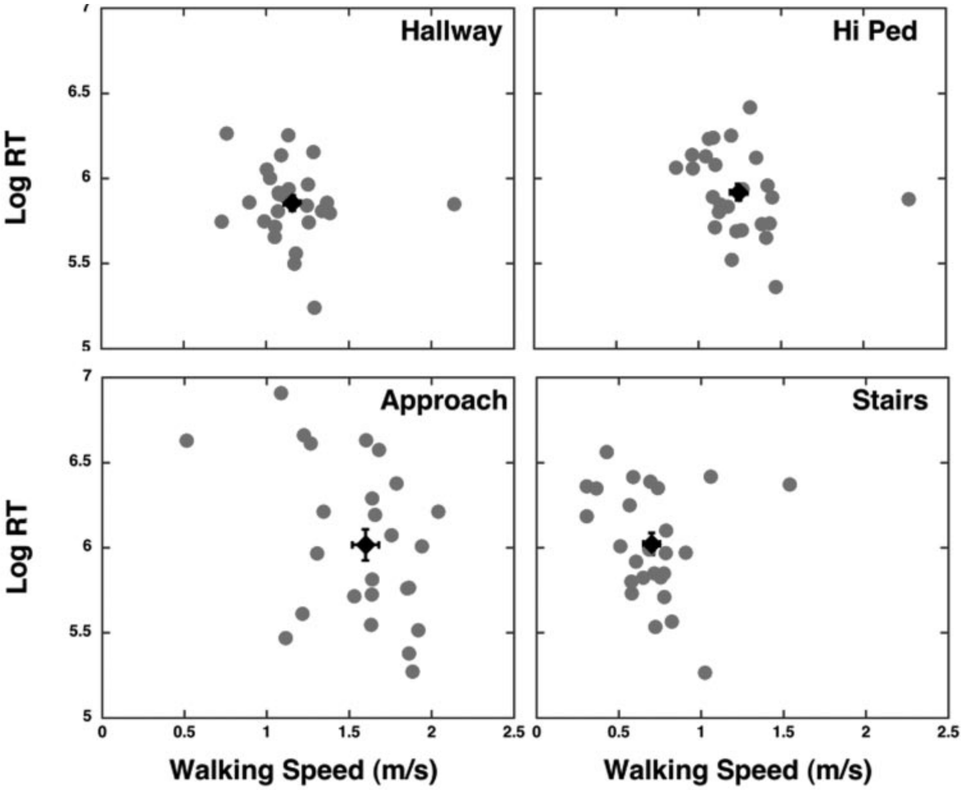

Figure 1. Log RT for each participant plotted against average walking speed in the four mobility segments (*circles*). The group means (*diamonds*) are plotted for each segment. Error bars, SEM.

The reported results are from analyses in which their data were excluded. (The findings did not change when the analyses were performed with their data included). With the two outliers excluded, the mean difference in the walking-speed distributions was 0.01 m/s, with a nonsignificant faster speed in the condition without the secondary task ($t_{25} = 0.91$, $P = 0.37$). In another *t*-test, performed on the overall average RT score, it was demonstrated that the order in which the subjects performed the secondary task did not affect the results ($t_{26} = 0.22$, $P = 0.83$).

The average difference in the mean baseline RT scores obtained at the beginning and end of the mobility route was 7.9 ms, with a longer RT score at the beginning of the route. A two-tailed, matched *t*-test, performed on the baseline RT scores showed that the difference was not significant ($t_{25} = -1.05$, $P = 0.30$). Therefore, the scores were averaged, and the mean baseline score was used as an adjustment factor for the log RT scores in the regression analyses. The average difference in the log RT scores for the two hallway tests, measured at the beginning and end of the route, was 0.1, with a longer RT score obtained at the end of the route. A two-tailed *t*-test, performed on the log RT scores, weighted by the number of samples in each test, indicated that the difference was not significant ($t_{50} = 1.58$, $P = 0.12$). Therefore the scores were averaged. The average number of vibrations (samples), time to complete the mobility segment, and RT scores are listed in Table 2.

Figure 1 shows the log RT for each participant plotted against average walking speed (meters per second) in the four mobility segments (circles), together with the group means for each segment (diamonds).

The Cronbach's α coefficient for the odd- versus even-numbered RT measures obtained in the high-pedestrian area was 0.89, providing support for the reliability of the secondary-task RT measures.

One of the ways we assessed the construct validity of the secondary-task RT scores was by determining the relationship between the log RT and the item measure scores derived from the perceived difficulty ratings (Fig. 2). The linear relationship between the two factors was significant ($P = 0.008$), and the best-fit line was: $\log \text{RT} = 5.97 + 0.112 \times \text{item measure}$.

Another way we assessed the construct validity of the secondary-task RT scores was by determining the relationship between the RT scores and the amount of visual field loss. We performed a linear regression analysis of the log of the RT scores averaged over the four environmental conditions on the MD score averaged over the two eyes, adjusting for age, gender, and log baseline RT. Table 3 shows the results of the analysis. The results showed a significant linear association

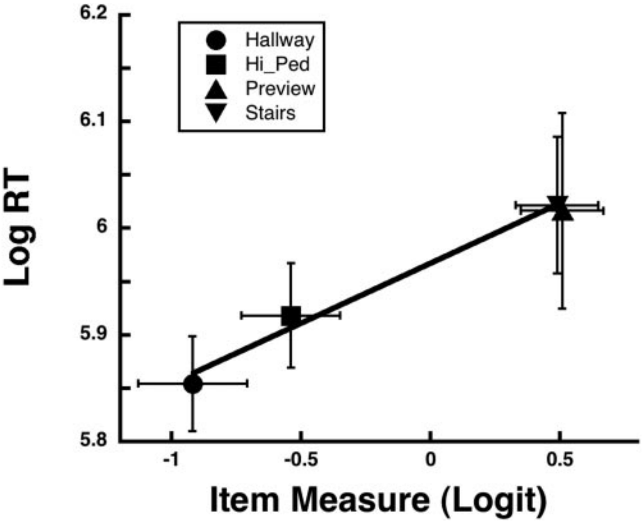

Figure 2. Log RT plotted against the item measure score derived from a Rasch analysis of perceived difficulty ratings for independent mobility in four comparable environments.[3] The higher the item measure the greater the perceived difficulty. The line is the best-fit linear function.

Table 3. Associations with the Log Average RT

Covariate	Estimate	SE	Standardized Coefficient	*P*
Log baseline RT	**0.685**	**0.126**	**0.710**	**<0.0001**
Gender	−0.018	0.034	−0.068	0.61
Age (per year)	0.003	0.001	0.201	0.11
Mean deviation (average)	**−0.013**	**0.004**	**−0.408**	**0.003**

Significant associations are in bold.

between the log RT and the MD score, with log RT increasing as the MD score decreased.

Table 4 shows the univariate associations between the log RT score in each of the four environmental areas and all measured vision variables as well as age, gender, and log baseline RT. The only factor, other than log baseline RT that was significantly associated with log RT was the average MD score, and it was significantly associated with log RT in all but the stairs segment.

To determine which vision factors were associated with RT while adjusting for all other vision factors, we performed a multiple linear regression analysis. To reduce the number of variables associated with the visual field assessment, we included only the average MD score. Age and gender were included in the multiple linear regression model, despite nonsignificance in univariate analyses, to account for any variations in the vision variables related to these factors. The results (Table 5) show that, apart from logMAR in the high-pedestrian segment, the average MD score was the only vision factor independently associated with the log RT score.

Table 4. Univariate Associations between Vision Measures and the Log RT Score for Each Mobility Segment

Segment/Variable	Coefficient	SE	Standardized Coefficient	*P*
Hallway				
Log baseline RT	**0.562**	**0.121**	**0.689**	**<0.0001**
Gender (male)	−0.021	0.035	−0.092	0.56
Age (y)	0.0001	0.002	0.007	0.96
LogMAR	0.108	0.174	0.099	0.54
Log peak CS	−0.080	0.159	−0.082	0.62
MD, average	**−0.009**	**0.004**	**−0.309**	**0.045**
CPSD, average	0.010	0.012	0.123	0.43
High-pedestrian				
Log baseline RT	**0.660**	**0.124**	**0.736**	**<0.0001**
Gender (male)	0.014	0.036	0.059	0.69
Age (y)	0.002	0.002	0.109	0.44
LogMAR	0.311	0.165	0.259	0.07
Log peak CS	−0.049	0.162	−0.045	0.77
MD, average	**−0.009**	**0.004**	**−0.333**	**0.024**
CPSD, average	0.006	0.011	0.080	0.59
Approach				
Log baseline RT	**0.757**	**0.307**	**0.450**	**0.02**
Gender (male)	−0.079	0.087	−0.171	0.38
Age (y)	0.006	0.005	0.194	0.30
LogMAR	0.486	0.420	0.215	0.26
Log peak CS	−0.102	0.394	−0.050	0.80
MD, average	**−0.024**	**0.010**	**−0.440**	**0.02**
CPSD, average	0.009	0.034	0.055	0.80
Stairs				
Log baseline RT	**0.695**	**0.194**	**0.590**	**0.002**
Gender (male)	−0.033	0.056	−0.102	0.56
Age (y)	−0.003	0.003	−0.142	0.40
LogMAR	0.305	0.270	0.193	0.27
Log peak CS	−0.089	0.253	−0.063	0.73
MD, average	−0.012	0.006	−0.314	0.07
CPSD, average	0.007	0.019	0.062	0.74

All factors adjusted for log baseline RT and vision factors are additionally adjusted for age and gender. Significant associations are in bold.

Table 5. Multivariate Associations of Vision Measures with the Log RT Score for Each Mobility Segment

Segment/Variable	Coefficient	SE	Standardized Coefficient	*P*
Hallway				
Log baseline RT	**0.718**	**0.148**	**0.837**	**<0.0001**
Gender (male)	0.041	0.042	0.177	0.34
Age (y)	0.001	0.002	0.107	0.49
LogMAR	0.068	0.228	0.062	0.77
Log peak CS	0.270	0.232	0.266	0.26
MD, average	**−0.011**	**0.005**	**−0.395**	**0.03**
High-pedestrian				
Log baseline RT	**0.696**	**0.124**	**0.828**	**<0.0001**
Gender (male)	0.038	0.035	0.167	0.30
Age (y)	0.002	0.002	0.136	0.31
LogMAR	**0.430**	**0.191**	**0.398**	**0.04**
Log peak CS	0.392	0.194	0.395	0.06
MD, average	**−0.009**	**0.004**	**−0.339**	**0.03**
Approach				
Log baseline RT	0.579	0.365	0.340	0.13
Gender (male)	−0.075	0.105	−0.163	0.48
Age (y)	0.006	0.005	0.227	0.25
LogMAR	0.492	0.562	0.225	0.39
Log peak CS	0.395	0.571	0.197	0.50
MD, average	**−0.024**	**0.011**	**−0.432**	**0.05**
Stairs				
Log baseline RT	**0.737**	**0.237**	**0.621**	**0.006**
Gender (male)	0.011	0.068	0.034	0.87
Age (y)	−0.002	0.003	−0.116	0.52
LogMAR	0.348	0.365	0.229	0.35
Log peak CS	0.435	0.371	0.311	0.26
MD, average	−0.013	0.007	−0.352	0.08

Significant associations are in bold.

Additional linear models were run that incorporated two-way interactions between the vision factors to explore further the relationship between vision and the log RT in each segment. Only in the stairs segment did the addition of the interaction terms significantly alter the main findings, as described in Table 5. With the interaction terms in the model, average MD was significantly associated with log RT ($P = 0.007$), and the two interactions average MD and logMAR ($P = 0.04$) and logMAR and logCS ($P = 0.002$) were significant.

The results of a repeated-measures ANOVA showed a significant main effect of mobility segment on the log RT score ($F_{3,25} = 6.07$, $P = 0.001$). Post hoc analyses revealed that the log RT in the stairs segment was significantly higher than the log RT of the high-pedestrian and hallway segments. The log RT in the approach-to-stairs segment was significantly higher than the log RT of the hallway segment. The log RT scores of the high-pedestrian and hallway segments were not significantly different from each other.

The results of a mixed-design ANOVA of log RT showed a significant main effect of subject group (early glaucoma, advanced glaucoma) ($F_{1,29} = 12.14$, $P = 0.002$) with the advanced-glaucoma group having longer log RTs (mean, 6.14) than did the early-glaucoma group (mean, 5.81). There was also a significant main effect of mobility segment ($F_{3,29} = 4.76$, $P = 0.008$). Post hoc analyses revealed the same ordering of log RT scores among the mobility segments as reported above for all the subjects with glaucoma. The only exception was that the difference between the log RT scores in the stairs and high-pedestrian segments ($F_{1,29} = 2.93$, $P = 0.09$), did not reach the 0.05 significance level. The interaction of mobility segment and subject group was not significant ($F_{3,29} = 1.18$, $P = 0.34$) indicating that log RT was dependent on the mobility segment in a similar manner for both early and advanced glaucoma.

DISCUSSION

The primary goal of this study was to validate the secondary-task RT measure as an estimate of the amount of mental effort required for independent travel. We first established the reliability of the RT measures by obtaining a Cronbach's α coefficient of 0.89 on the odd- versus even-numbered adjusted RT scores from the high-pedestrian area. Construct validity was supported in two ways: (1) The secondary-task log RT scores were linearly related to the item measure scores for similar environments. The item measure scores were derived from a Rasch analysis of perceived difficulty ratings obtained from a separate group of persons with glaucoma. We reasoned that situations reported as difficult should have slower RT scores than those reported as being less difficult. (2) The log RT scores were linearly related to the magnitude of visual field loss as indexed by the MD score. We reasoned that, since self-reports of perceived difficulty were shown to be correlated with degree of visual field loss,[2,3] the average RT score should be associated with the magnitude of visual field loss.

Of the four environmental conditions that we tested, the two mobility segments that required the most mental effort for walking were the approach-to-stairs and stairs. The hallway required the least amount of mental effort, and the high-pedestrian area required an amount of mental effort somewhere in between. The finding that the hallway required the least amount of mental effort is not surprising. Many visual cues are available to guide one's walking down a corridor. For example, one could walk so as to keep the optic flow that is generated during self-motion[21] equalized with respect to one's midline.[22] People with actual[23] and simulated[24] peripheral visual field loss are able to extract heading direction from optic flow and can use optic flow to guide mobility.[25]

The absence of obstacles in the hallway segment, which also probably contributed to the ease in walking this segment, contrasts with that in the high-pedestrian area. Walking in the high-pedestrian area would require careful scanning of the environment to locate the obstacles (people) to avoid collision. Kuyk et al.[12] have shown that obstacle avoidance is linearly related to scanning ability and visual field extent. To ensure obstacle detection within a scene, people with small visual fields would have to compensate for the reduced information within a glance, perhaps by taking more "snapshots" and piecing them together to estimate distance. In the approach-to-stairs and stairs segments, the stairs and handrail were within the line of sight but were located in an open atrium rather than in a stairwell, with low contrast between the floor and the stairs. The fact that visual search performance is adversely affected in peripheral visual field loss[26] and that the risk of falling is high in both of these segments probably contributes to their associated increase in required mental effort. Walking on stairs has long been identified by orientation and mobility specialists as one of the most challenging aspects of travel.[27]

The MD score and logMAR were the only vision function measures linearly associated with the log RT score. The association of the MD score with the RT score is not surprising, given that most measures of mobility performance are associated with visual field measures.[2,3,9,11,12,28–34] However, the same is not true of visual acuity (but see Brown et al.[35]). In a self-report study,[3] logMAR and MD both correlated significantly with the subjects' average *perceived ability* for independent mobility. One might deduce from these two studies that although performance is not associated with visual acuity, one's perception of the difficulty and amount of mental effort required for independent travel are associated with it.

It was surprising that age was not a significant predictor of the log RT score in any of the mobility segments. The ages of the participants spanned a wide range: 24.8 to 84.3 years. Although it is possible that the visual field effect swamped any effect due to age, this explanation is unlikely to explain the lack of correlation of age with the baseline RT estimate ($r = -0.08$). The baseline RT scores ranged from 164 to 469 ms (mean, 285). We have no explanation for the lack of an age effect with the baseline RT score.

When the secondary-task method is used, the choice of the stimulus and the task are critical. In a previous secondary task study with mobility performance an auditory stimulus was used.[16] However, a concern in that study was whether the stimulus might interfere with the ambient sounds that occur in natural settings (music and conversation indoors and vehicle noise outdoors). The selection of a tactile stimulus avoids this potential problem. In addition to selecting the secondary task stimulus, one must also choose the appropriate task so that the level of difficulty falls within a range that is not so taxing that it cannot be performed at all or that it interferes with performance on the primary task and not so effortless that a response becomes automatic. It is also important that the choice of secondary task does not interfere with primary-task information. Findings in the present study demonstrate that a tactile stimulus is appropriate as a secondary-task stimulus for mobility. Finally, the frequency at which a secondary-task response is required must be appropriately chosen, to obtain a sufficient number of samples. Alternatively, one could have subjects respond to some kind of code or a break in a continuous stimulus stream.

The measurement of the mobility of the visually impaired poses many challenges, including what should be measured and how it should be measured. When severe visual impairment is present, strategies that involve obstacle courses and the measurement of contacts with obstacles can provide meaningful data. When significant vision is remaining, counting mobility events such as contacts with obstacles is less useful, since these events are rare. Our results demonstrate that the secondary-task methodology is sensitive enough to detect differences in mental effort as a function of environmental complexity in persons with mild or severe visual field loss due to glaucoma. Whether it is also able to differentiate degrees of mental effort in persons with full vision remains to be seen.

Measures of mental effort provide a complementary source of information to the traditional measures. It is a continuous variable and, as demonstrated in this study, is sensitive to different environmental characteristics and to degrees of visual field loss. Measures of mental effort can be effective for documenting who may benefit from professional intervention, and it may also be useful for evaluating the effectiveness of an intervention. Clinicians want to know who needs mobility instruction and how much instruction they need. The measure of mental effort has the potential to describe objectively the type of patient who would benefit from mobility instruction. In addition, it may be useful as a measure for describing progress that occurs through instruction and for documenting when services can be terminated.

Acknowledgments

The authors thank Julie Stahl for help in data collection and analysis and Harry Quigley for clinical diagnosis.

References

1. Long RG, Rieser JJ, Hill EW. Mobility in individuals with moderate visual impairments. *J Vis Impair Blind*. 1990;84:111–118.
2. Turano KA, Geruschat DR, Stahl JW, Massof RW. Perceived visual ability for independent mobility in persons with retinitis pigmentosa. *Invest Ophthalmol Vis Sci*. 1999;40:865–877.
3. Turano KA, Massof RW, Quigley HA. A self-assessment instrument designed for measuring independent mobility in RP patients: generalizability to glaucoma patients. *Invest Ophthalmol Vis Sci*. 2002;43:2874–2881.
4. Szlyk J, Arditi A, Coffey Bucci P, Laderman D. Mobility problems related to vision loss: perceptions of mobility practitioners and persons with low vision. *J Vis Impair Blind*. 1990;84:61–66.
5. Nelson p, Aspinall P, O'Brien C. Patients' perception of visual impairment in glaucoma: a pilot study. *Br J Ophthalmol*. 1999;83: 546–552.
6. Clark-Carter DD, Heyes AD, Howarth CI. The efficiency and walking speed of visually impaired pedestrians. *Ergonomics*. 1986;29: 779–789.
7. Beggs WD. How mobility officers assess need for mobility training. *Int J Rehabil Res*. 1990;13(4):281–290.
8. Soong GP, Lovie-Kitchin JE, Brown B. Measurements of preferred walking speed in subjects with central and peripheral vision loss. *Ophthalmic Physiol Opt*. 2004;24(4):291–295.
9. Marron JA, Bailey IL. Visual factors and orientation-mobility performance. *Am J Optom Physiol Opt*. 1982;59:413–426.
10. Geruschat DR, De l'Aune W. Reliability and validity of O & M instructor observations. *J Vis Impair Blind.* 1989;9:457–460.
11. Kuyk T, Elliott JL, Fuhr PS. Visual correlates of mobility in real world settings in older adults with low vision. *Optom Vis Sci*. 1998;75:538–547.
12. Kuyk T, Elliott JL, Fuhr PS. Visual correlates of obstacle avoidance in adults with low vision. *Optom Vis Sci*. 1998;75(3):174–182.
13. Kuyk T, Elliott JL, Biehl J, Fuhr PS. Environmental variables and mobility performance in adults with low vision. *J Am Optom Assoc.* 1996;67:403–409.
14. Kahneman D. *Attention and Effort.* Englewood Cliffs, NJ: Prentice-Hall; Inc. 1973.
15. Shingledecker CA. Measuring the mental effort of blind mobility. *J Vis Impair Blind*. 1983;77:334–339.
16. Turano KA, Geruschat DR, Stahl JW. Mental effort required for walking: effects of retinitis pigmentosa. *Optom Vis Sci*. 1998;75: 879–886.
17. Ferris FL, Kassoff A, Bresnick G, Bailey I. New visual acuity charts for clinical research. *Am J Ophthalmol*. 1982;94:91–96.
18. Bailey IL, Bullimore MA, Raasch TW, Taylor HR. Clinical grading and the effects of scaling. *Invest Ophthalmol Vis Sci*. 1991;32: 422–432.
19. Pelli DG, Robson JG, Wilkens AJ. The design of a new letter chart for measuring contrast sensitivity. *Clin Vision Sci*. 1988;2:187–199.
20. Campbell DT, Fiske DW. Convergent and divergent validation by the Multitrait-Multimethod Matrix. *Psychol Bull*. 1959;56:81–105.
21. Gibson JJ. *Perception of the Visual World.* Boston, MA: Houghton Mifflin; 1950.
22. Duchon AP, Warren WH. A visual equalization strategy for locomotor control: of honeybees, robots, and humans. *Psychol Sci*. 2002;13:272–278.
23. Li L, Peli E, Warren WH. Heading perception in patients with advanced retinitis pigmentosa. *Optom Vis Sci*. 2002;79:581–589.
24. Cornelissen FW, Dobbelsteen J. Heading detection with simulated visual field defects. *Vis Impair Res*. 1999;1:71–84.
25. Turano KA, Yu D, Hao L, Hicks J. Optic-flow and egocentric-direction strategies in walking: central vs peripheral visual field. *Vision Res*. 2005;45:3117–3132.
26. Cornelissen FW, Bruin KJ, Kooijman AC. The influence of artificial scotomas on eye movements during visual search. *Optom Vis Sci*. 2005;82(1):27–35.
27. Smith AJ, De l'Aune W, Geruschat DR. Low vision mobility problems: perceptions of O&M specialists and persons with low vision. *J Vis Impair Blind*. 1992;86:58–62.
28. Lovie-Kitchin J, Mainstone J, Robinson J, Brown B. What areas of the visual field are important for mobility in low vision patients? *Clin Vis Sci*. 1990;5:249–264.
29. Haymes S, Guest D, Heyes A, Johnston A. Mobility of people with retinitis pigmentosa as a function of vision and psychological variables. *Optom Vis Sci*. 1996;73:621–637.
30. Geruschat DR, Turano KA, Stahl JW. Traditional measures of mobility performance and retinitis pigmentosa. *Optom Vis Sci*. 1998; 75:525–537.
31. Turano KA, Rubin GS, Quigley HA. Mobility performance in glaucoma. *Invest Ophthalmol Vis Sci*. 1999;40:2803–2809.
32. Turano KA, Broman AT, Bandeen-Roche K, et al. Association of visual field loss and mobility performance in older adults: Salisbury Eye Evaluation Study. *Optom Vis Sci*. 2004;81:298–307.
33. Broman AT, West SK, Munoz B, Bandeen-Roche K, Rubin GS, Turano KA. Divided visual attention as a predictor of bumping while walking: the Salisbury Eye Evaluation. *Invest Ophthalmol Vis Sci*. 2004;45(9):2955–2960.
34. Patel I, Turano KA, Broman AT, Bandeen-Roche K, Munoz B, West SK. Measures of visual function and percentage of preferred walking speed in older adults: the Salisbury Eye Evaluation Project. *Invest Ophthalmol Vis Sci*. 2006;47(1):65–71.
35. Brown B, Brabyn L, Welch L, Haegerstrom-Portnoy G, Colenbrander A. Contribution of vision variables to mobility in age-related maculopathy patients. *Am J Optom Physiol Opt*. 1986;63: 733–739.