Eye Movements, Strabismus, Amblyopia, and Neuro-Ophthalmology

Optokinetic Nystagmus Suppression as an Index of the Allocation of Visual Attention

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Purpose. To use the suppression of optokinetic nystagmus (OKN) as an objective measure of subjects' ability to distribute their visual attention to different elements—static or dynamic, simple or complex—in their visual environment.

Methods. Large-field, constant-velocity projected images, along with a stationary central fixation target were presented to 25 young participants (13 women). Images were either black O's with a few X's or red C's, blue T's, and a few red T's, with the X's and red T's as the search targets. Stationary targets at either 0° or ±12.5° were either blinking squares or a rapid succession of colored shapes—blinks or green stars were the target events. Central fixation was maintained at all times. OKN gain was calculated for all tasks and analyzed in a mixed 4-way ANOVA, with the sex of the subjects as the group variable and dynamism, location, and complexity as within-subject effects.

Results. There was no effect of sex; all three main within-subject effects were significant, as were the two-way interactions between them and an interaction between dynamism and sex. The most striking result was that there was little difference across static tasks but that dynamic tasks showed significantly more OKN breakthrough, particularly for the complex search presented centrally.

Conclusions. In this group of normal-sighted young subjects, OKN breakthrough was sensitive to a range of stimulus characteristics. This finding allows a single outcome measure to be used across a wide range of possible tasks and may be useful in assessing the effects of age and disease. (*Invest Ophthalmol Vis Sci.* 2011;52:462–467) DOI:10.1167/iovs.10-6016

To extract meaning from the visual world around us, we must be able to pay appropriate attention to it. Core to this ability is the differentiation of objects of interest from other elements of the visual environment. This facility is initially achieved by a stimulus-driven (or bottom-up) process, in which the saliency of objects is determined by the automatic processing of discrete features,[1,2] after which comes a volitional (or top-down) process, dependent on the requirements of the specific task.[3] Bottom-up processing produces maps of simple features (color, orientation, and direction) organized in space, allowing unique features to be detected in parallel with no attentional limits, in a pop-out mechanism.[4] This mechanism is insufficient for the detection of multifeature targets, where target and distracter share the same features. For this complex task, top-down serial processing is required, which involves binding together the different features into a representation of the object.[3] There is evidence to suggest that these processing systems lead to the creation of an integrated saliency map with the two processes converging in lateral intraparietal cortex,[5,6] which, in turn, may provide a topographic representation of the relative saliency, or attention-drawing power, of objects in the visual environment.[1,7,8]

In the visual field, relevant features within the locus of attention are enhanced, whereas detail outside of this locus is sacrificed. Thus, much of the information received by the peripheral receptors is filtered out, as selective attention acts to limit the amount of information reaching the higher processing centers of the brain.[9] In a study of orientation-selective, attentional modulation of neurons, it was demonstrated that within the same retinotopic space, the response of neural subpopulations is increased for the attended features.[10] This enhancement in sensitivity to an attended feature is also evident for nonattended spatial locations.[11] Studies have also shown that unexpected objects often fail to capture attention.[12] This phenomenon of inattentional blindness occurs because of a reduction in saliency of unattended stimuli.

The enhancement of attended features has led to the idea of a spotlight of attention.[13] When this spotlight is not coincident with the point of fixation, the subject is said to be using covert attention: the phenomenon of looking out of the corner of one's eye.[13] Attention has been further described as being distributed spatially by zoom-lens and multiple-spotlight models.[14–16]

The ability to divide visual attention, a component of multitasking, is an essential skill for daily living in modern society. It is necessary for activities such as playing sports, driving, and navigating a footpath. It is susceptible to impairment by normal aging processes,[17] as well as such disorders as stroke,[18] ADHD (attention deficit hyperactivity disorder),[19] and traumatic brain injury.[20] Because of the finite nature of attention, these impairments may only manifest with increased task difficulty.[21]

Assessment of the integrity of a subject's attentional resources is particularly important in detecting those whose attentional resources break down under heavier processing loads, but function effectively in low-demanding environments. These individuals are unlikely to be identified as having a problem by other clinical assessment techniques, leaving them without the opportunity to receive aid.

The useful field of view (UFOV) test is a currently available assessment technique for examining attentional resources.[22,23] It is used to assess a subject's ability to correctly identify the location of peripherally located static stimuli, while fixating a central stimulus. Unfortunately, the range of test parameters to be varied is quite limited. It is desirable to be able to assess the ability to direct attentional resources to stimuli that vary in complexity and location and that were either moving or static, thus better mirroring the visual environments we encounter in real life.

Another approach to measuring divided attention was proposed by Williams et al.,[24] involving the use of an optokinetic nystagmus (OKN)–inducing stimulus. The stimulus, a cloth

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cylinder surrounding the subject, creates the horizontal motion of essentially all the visual field. In the absence of a fixation target, normal subjects produce an involuntary OKN in response to the moving visual field. OKN involves a slow-phase eye movement in the direction of the stimulus and a fast-phase, resetting movement in the opposite direction. The moving field may be actively tracked (look OKN) or it may be responded to passively as the subject stares straight ahead (stare OKN).[25]

Suppression of the OKN response is achieved in normal subjects by attentively fixating a stationary element in the otherwise moving visual field. Any reduction in attention to the fixation stimulus would be expected to lead to a subsequent reduction in the subject's ability to suppress the OKN response. The degree of OKN breakthrough can be easily measured in terms of gain (eye velocity/OKN stimulus velocity). The cylindrical cloth curtain as a stimulus has the advantage of being visually compelling but the considerable disadvantage of being unmodifiable. This configuration made it impossible to examine the effects of varying the characteristics of the moving stimulus or to superimpose on it stationary elements that could serve as loci of attention.

In this study, we sought to further explore the ability of a normal, young population to attend to visually divided stimuli of varying complexity. Although we examined some of the questions raised by Williams et al.,[24] we did not attempt to replicate their wide range of ages. We hypothesized that the ability to divide attention would decrease with increasing stimulus complexity and increasing spatial spread. We also expected that OKN suppression would be more affected by attention to dynamic than to static elements of the test stimuli. We further hypothesized that the females would exhibit more breakthrough than the males, as recent studies have suggested that females do more poorly on tasks involving distribution of spatial attention.[26,27] An eventual goal of this study was to develop a potential clinical tool for assessing the ability to divide attention, and for this reason computer-based stimuli offer much more scope for customizing stimulus characteristics. The purpose of this study was to further the development of clinical assessment tests for divided attention.

METHOD

Subjects

Twenty-five subjects were tested (13 women), aged from 21 to 26 years. All subjects had best corrected visual acuity of 6/6 or better. During testing, all subjects had vision of 6/6 uncorrected or with contact lenses except for one subject who was not a contact lens wearer and was tested without glasses when his vision was 6/48 (Snellen), after confirming that he could still clearly discriminate the various targets. Color vision testing (Ishihara test) revealed all but one subject to have normal color vision; this subject successfully demonstrated the ability to differentiate between the colors used in the study. All subjects had full visual fields to confrontation with finger counting. They had no manifest strabismus, no clinically apparent defect in ocular motility, and no nystagmus. They had no history of head trauma, psychosis, or any vestibular, ocular, or neurologic disease, with the exception of one subject with paroxysmal kinesogenic choreoathetosis (PKC). Two subjects were found to be taking medication potentially affecting eye movements (lithium and carbamazepine [Tegretol, Novartis, Camberley, UK] for PKC); as none of their results were outliers with respect to the distributions of results, they remained in the study. All subjects gave written informed consent. The test protocols were approved by the Human Research Ethics Committee of The University of Melbourne (HREC 0931666.1) and adhered to the tenets of the Declaration of Helsinki.

Eye Movement Recording

Horizontal eye movements were recorded by binocular infrared oculography (Microguide, Downers Grove, IL) with a bandwidth of DC-100 Hz and a system sensitivity of 1 minute of arc horizontally within ±30° of the center on the horizontal plane.[28] The positions of the eyes and the push-button responses were displayed on a cathode ray oscilloscope and were digitized at 1000 Hz. The recording system was calibrated with a range of ±15° before recording. A program was created in commercial software (MatLab. ver. 7.0.4; The MathWorks, Natick, MA) data acquisition.

Optokinetic Stimulus

Each subject was seated in front of a white projection screen 1.55 m from the plane of the infrared sensors on the eye tracker. Optokinetic stimuli were projected, via an ultra–short-throw projector (WT610; NEC, London, UK) onto the screen at a frequency of 60 Hz and resolution of 1024 × 768. The stimuli each had a width of 1.83 m and a height of 1.36 m, subtending 61.1° × 47.4° at the plane of the infrared sensors of the eye tracker, thus serving as a large if not full-field stimulus.[29] Commercial software (MatLab 2009a) and Psychophysics Toolbox[30,31] was used to create a program that presented the fixation targets and translated the optokinetic stimuli at an angular speed of 25° per second, as measured at primary position.

The first optokinetic stimulus (TC) was a computerized copy of the curtain used by Williams et al.[24]: white with columns of colored T's and C's, 20.8 cm (7.7°) apart (Fig. 1, left). Each letter had a line thickness one fifth the size of the letter. The T's subtended 5.0° × 5.7° at the eye and the C's 5.4° × 5.7°. Each column consisted of blue T's and red C's in random order, whereas the horizontal row at eye level included three unequally spaced red T's.

The second optokinetic stimulus (XO) was white with columns of black X's and O's (Fig. 1, right), with X's replacing the red T's of the previous stimulus; other letters were replaced by O's, with the same angular subtense as the C's of the previous stimulus. The test space was kept in dim lighting and was surrounded by black curtains.

Static Stimuli

A green square subtending 1.4° at the eye was used as a simple stimulus at fixation and in the periphery. A series of pseudorandomly

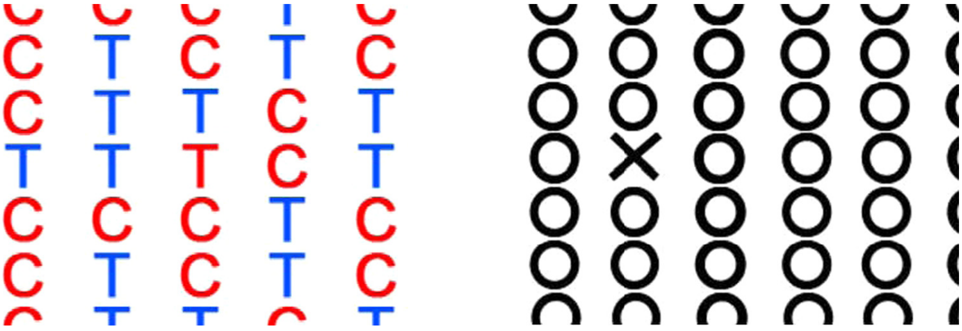

FIGURE 1. *Left*: TC optokinetic stimulus, comprising *blue* T's, *red* C's, and one *red* T at eye level. *Right*: XO optokinetic stimulus, comprising *black* O's and one *black* X at eye level.

FIGURE 2. Complex fixation stimuli: *orange* and *green circles*, *squares*, and *stars*, presented at two per second.

changing shapes, including squares, circles, and stars colored either green or orange, served as more complex stimuli at these locations (Fig. 2). To aid resolution in the periphery, these shapes were enlarged by 50% along both meridians in the periphery (±12.5°).[32,33] Shapes changed every 0.5 ± 0.2 seconds.

Procedure

After the subjects' ability to produce normal stare OKN in both directions was confirmed, eight tasks were performed, each of 30 seconds duration, with a break of at least 10 seconds between tasks. Tasks were run in fixed order. For peripherally attended targets, the optokinetic stimulus moved centripetally, since pilot studies had shown that subjects were likely to follow centrifugally moving targets as they went away from primary position. The tasks are described in Table 1.

Analysis

Analysis was performed offline (MatLab, ver. 7.0.4; The MathWorks) with the best-calibrated eye analyzed for each subject. The eye position signal was digitally differentiated and low-pass filtered at 30 Hz, with blinks and saccadic intrusions manually removed from the analysis. The data from the first 5 seconds were omitted to ensure steady state performance. Mean velocity was divided by angular velocity of the optokinetic stimulus, to determine the mean gain for each task; thus, the higher the gain, the more the OKN breakthrough.

Initial analysis was performed with a five-way, mixed-measures analysis of variance (ANOVA), with within-subject variables of stimulus direction (left/right), complexity (blinking spot and X's/shape sequence and red T's), dynamism (moving/static), and location (central/peripheral). As the only significant effect of direction was one interaction for one task (central T), we collapsed the data across direction and subsequent analyses were performed with a four-way, mixed-measures ANOVA, with a significance level of 0.05. To examine the effects of the individual factors, we calculated the marginal means, averaging across each of the within-subject variables. The significant marginal means are summarized in Table 2.

The accuracy of the button presses was subsequently analyzed with a one-way, repeated-measures, nonparametric Friedman ANOVA. Button press data were lost for the last male subject tested because of a technical failure and thus were not included in the analysis.

RESULTS

Clear differences were found between the dynamic and static tasks. While all the static tasks had quite similar gains (Fig. 3), OKN suppression varied significantly when complexity and location attended to were varied in the dynamic tasks. For all within-subject comparisons between static and dynamic tasks at all levels of interaction, OKN breakthrough was higher for the dynamic tasks (Table 2). As seen in Figure 3, complex dynamic tasks showed higher gains than simple ones, and central dynamic tasks also showed more breakthrough than peripheral ones. Thus, OKN was most poorly suppressed on the complex central task (i.e., detecting the passage of red T's past the fixation point), not when attention was spatially distributed. The within- and between-subject interactions are summarized in Table 3. In the between-subjects analysis, sex showed no significant effect, although it did show a significant interaction with dynamism (Table 3, Fig. 4).

The subjects' performance in detecting the targeted stimulus changes (e.g., blinking spots, passing X's) was excellent across tasks, with <2% of trials scoring below 90% correct. Friedman's nonparametric repeated measures ANOVA showed a significant main effect for task ($P < 0.05$), but post hoc testing with Dunn's multiple-comparison test showed no significant pair-wise differences.

DISCUSSION

This study took advantage of the flexibility of computer-based stimulus generation to extend the work of Williams et al.[24] in several directions. The ability to modify the OKN stimulus allowed us to vary the detection task between the simple pop-out search required for detecting a few X's in a mass of O's and the complex conjunction search needed to find the few red T's among a multitude of blue T's and red C's. We were also able to vary both the fixation and peripheral targets between a simple spot occasionally blinking off and a rapidly presented series of symbols that varied in shape and color. The influence of the separate stimulus parameters and their interactions (discussed below) allowed us to examine separately the extent to which OKN breakthrough is influenced by directing attention overtly or covertly to static and dynamic stimuli, whose target features required markedly different levels of effort to identify successfully. As all the subjects in the present study were young, this was not an attempt to use computer-based stimuli to replicate those used by Williams et al. on the effects of age on OKN suppression during a covert attention task. The effects of the individual stimulus parameters will be discussed individually as well as in regard to their interactions.

TABLE 1. Tasks

Task Name	Optokinetic Stimulus	Fixation Target (Central)	Attended Target	Feature to Be Detected	Number of Features to Be Detected
Central spot	TC	Spot	Central Spot	Spot flashes off	13
Central T	TC	Spot	Central red T	Red T passes central spot	11
Central shapes	TC	Shapes	Central shapes	Green star appears centrally	11
Central X	XO	Spot	Central X	X passes central spot	12
Peripheral spot	TC	Spot	Peripheral Spot	Peripheral spot flashes off	13
Peripheral T	TC	Spot	Peripheral red T	Red T passes peripheral spot	11
Peripheral shapes	TC	Spot	Peripheral shapes	Green star appears peripherally	10
Peripheral X	XO	Spot	Peripheral X	X passes peripheral spot	11

Subjects were asked to fixate centrally and press a button when a specific change in the attended stimuli occurred.

TABLE 2. Estimated Marginal Means of Significant Main Effects and Two- and Three-way Interactions

Effect 1	Level	Effect 2	Level	Effect 3	Level	Mean	SE
Complexity	Simple					0.088	0.006
	Complex					0.114	0.009
Location	Central					0.115	0.009
	Peripheral					0.087	0.006
Dynamism	Static					0.072	0.004
	Dynamic					0.130	0.011
Sex	Female	Dynamism	Static			0.069	0.006
			Dynamic			0.144	0.015
	Male		Static			0.076	0.006
			Dynamic			0.116	0.016
Complexity	Complex	Location	Central			0.096	0.007
			Peripheral			0.079	0.005
	Simple		Central			0.133	0.011
			Peripheral			0.095	0.008
Complexity	Simple	Dynamism	Static			0.072	0.004
			Dynamic			0.104	0.009
	Complex		Static			0.073	0.004
			Dynamic			0.156	0.014
Location	Central	Dynamism	Static			0.076	0.005
			Dynamic			0.153	0.014
	Peripheral		Static			0.068	0.004
			Dynamic			0.106	0.009
Complexity	Simple	Location	Central	Dynamism	Static	0.074	0.005
					Dynamic	0.119	0.012
			Peripheral		Static	0.070	0.004
					Dynamic	0.088	0.007
	Complex		Central		Static	0.078	0.005
					Dynamic	0.187	0.018
			Peripheral		Static	0.067	0.004
					Dynamic	0.124	0.012

Stimulus Dynamism

In this study, dynamic stimuli elicited greater breakthrough than static stimuli, consistent with the hypothesis that directing attention to the moving stimulus increases activation of the motion-processing areas of the brain, making the optokinetic stimulus more salient. The literature shows that attending to moving stimuli causes an increase in gain for direction-sensitive neurons both within the locus of attention and the rest of the visual field.[11,34,35] For a stimulus containing both moving and stationary dots, attending to the moving elements significantly increased activity seen on functional magnetic resonance imaging (fMRI) in areas MT (middle temporal) and MST (middle superior temporal).[36] Thus, it is likely that attending even to a localized feature of the moving optokinetic stimulus enhances the neuronal response to the entire stimulus, making suppression more difficult.

An interaction was observed between dynamism and location for both simple and complex tasks. The increased break-

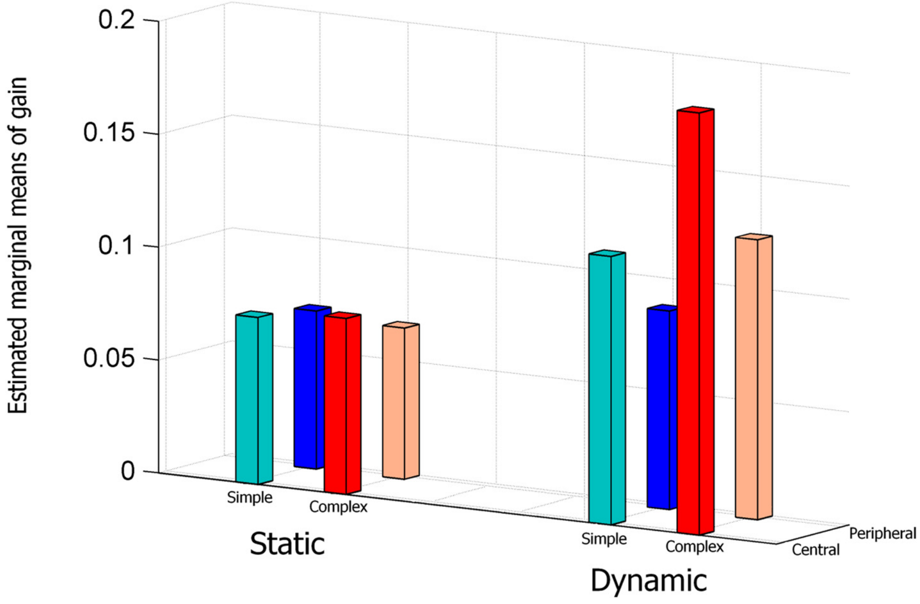

FIGURE 3. Estimated marginal means of OKN gain for central and peripheral locations, both simple and complex, for static and dynamic tasks.

TABLE 3. Within- and Between-Subject Effects

Effect	*F*	*df*	*P*
Complexity	***36.817***	***1.000***	***0.001***
Complexity × sex	1.022	1.000	0.323
Location	***34.098***	***1.000***	***0.000***
Location × sex	0.132	1.000	0.720
Dynamism	***47.102***	***1.000***	***0.001***
Dynamism × sex	***4.354***	***1.000***	***0.048***
Complexity × Location	***12.756***	***1.000***	***0.002***
Complexity × location × sex	0.536	1.000	0.472
Complexity × Dynamism	***35.974***	***1.000***	***0.001***
Complexity × dynamism × sex	0.226	1.000	0.639
Location × dynamism	***24.215***	***1.000***	***0.001***
Location × dynamism × sex	0.200	1.000	0.659
Complexity × location × dynamism	***4.322***	***1.000***	***0.049***
Complexity × location × dynamism × sex	0.117	1.000	0.735

Significant effects are bold and italic.

through elicited by dynamic stimuli was more pronounced for central than peripheral targets. Centrally located and dynamic stimuli were shown to elicit greater breakthroughs than peripherally located and static stimuli, respectively. These results appear to support the hypothesis that the different features of an object have an additive effect on depleting attentional reserves.

Stimulus Location

In this study, central stimuli elicited greater breakthrough than peripheral stimuli, in contrast to the original hypothesis that breakthrough would increase with increasing attentional eccentricity. There are several possible explanations for this unexpected result. First, the projection used was not full field and so relocating attention peripherally could have increased awareness of the edges of the image, reducing the saliency of the optokinetic stimulus. This reduction in peripheral saliency of the stimulus may reduce the OKN drive.[37] The low rate of linear vection reported when subjects were debriefed after the experiment was consistent with this. In addition, increasing the stimulus eccentricity to 12.5° may not be enough to stress the attentional reserves of a normal young population. This hypothesis is supported by the findings of Kosslyn et al.[38] in a study involving a simple detection task, which revealed no significant difference in performance with increased spacing of targets for a young population. There was, however, an effect noted for the older population tested.

Neville and Lawson[39] note that attention to central and peripheral visual space elicit activity in different cortical regions, with central attention increasing activation in the foveal region of striate cortex and peripheral attention activating contralateral parietal cortex. In an ERP (event-related potentials) study of centrally focused versus divided attention, Miniussi et al.[40] found that foveal stimuli were processed faster and more efficiently when attention was concentrated at the center than when it was divided. If a similar enhancement of foveal information processing occurred when our subjects had to detect the passage of the target letter across the fixation point, this enhancement might account for the increase in OKN breakthrough in this task.

Stimulus Complexity

Complex stimuli elicited significantly greater breakthrough than did simple stimuli. Post hoc analyses showed that this response was only seen with dynamic stimuli. This may have been part of a continuum that began when directing attention to the moving stimulus made it more salient and harder to suppress. When the search task performed on this dynamic stimulus was difficult, the additional attentional demands further increased its salience and made suppression more difficult yet. This finding supports the original hypothesis that complexity has an adverse effect on the ability to suppress OKN. The failure of the complex static task to affect OKN breakthrough may be due to the reduced proportion of available attentional resources required for this task. Making it more demanding, perhaps by using more simultaneously presented shapes at different locations or by making the stimuli more similar, may eventually impair OKN suppression.

Interaction Effects

All the independent variables had significant interactions. This result supports the hypothesis that they are additive in their ability to exhaust attentional reserves. The interactions appear to indicate that dynamism has a greater effect than either location or complexity on depleting attentional reserves and hence on the ability to divide attention.

Effect of Sex

In this study significant effect of the sex of the subject was shown in the interaction between the subject's sex and dynamism. As seen in Figure 4, the men produced less breakthrough with dynamic but not with static stimuli. Previous research has demonstrated that the brain is specialized according to sex.[41] In a recent study,[26] females did significantly more poorly on the UFOV task. The complexity of the UFOV is considerably greater than that of our static tasks. Rubia et al.[27]recently reported poorer performance by females on a visual–spatial oddball task, with concurrent differences in brain activation patterns. These findings may be consistent with the superior performance of males on our dynamic tasks.

CONCLUSIONS

We found that OKN breakthrough may be a sensitive indicator of how visual attention is allocated. An advantage lies in having the same outcome measure—OKN gain—used independent of the ways in which task demands are varied. Further studies using more complex and more spatially distributed targets, as well as evaluation of older normal subjects and clinical groups, will allow us to further evaluate the possible clinical utility of this technique.

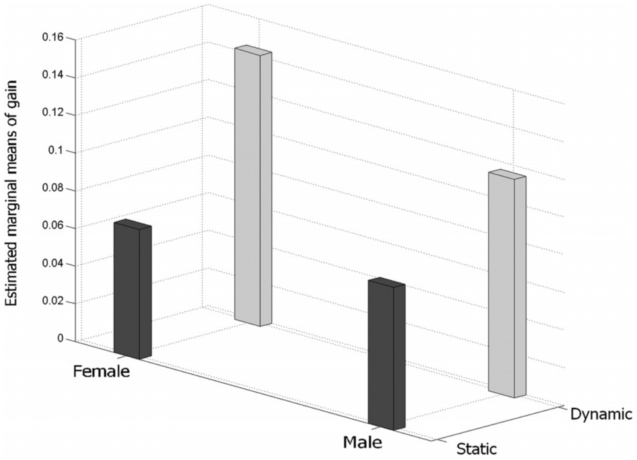

FIGURE 4. Estimated marginal means for static and dynamic tasks with respect to the sex of the subject.

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