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ESTUDIO PSICOFISICO Y PSICOFISIOLOGICO DE LA ATENCION A EVENTOS: INFLUENCIA DE LA ORGANIZACION PERCEPTUAL

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A los sujetos experimentales

Síntesis

La atención visual es uno de los temas de mayor interés en la psicología y neurociencias contemporáneas, y quizás el de más fructífera cooperación entre ambas disciplinas hoy en día. El modelo teórico dominante asemeja la atención a una 'linterna' que selecciona regiones del campo visual, priorizando la información de allí proveniente en detrimento de otras zonas de la escena, evitando así una sobrecarga de información al sistema nervioso. Este foco de atención, por tanto, funcionaría sobre una representación puramente espacial, y podría desplazarse rápidamente de un lugar a otro, llevando a cabo un procesamiento serial. También se concibe que sólo esta selección espacial puede actuar filtrando información en las estaciones tempranas de la vía visual. Según este modelo, la atención es independiente de la organización perceptual de la escena en objetos.

En años recientes se ha comenzando a cuestionar este punto de vista. Esta tesis contradice, experimentalmente, todos sus postulados. Para ello se desarrolló un nuevo diseño experimental: las Transformaciones Seriales Rápidas de Objetos (TSRO), el cual permite explorar el efecto de la organización perceptual de la escena, es decir, su estructuración en objetos, sobre el control de la atención. Se demuestra que la metáfora de la linterna no siempre es válida, y que, en diversas condiciones, la selección de la información en una escena no sólo se basa en el espacio, sino también en la organización de la misma en objetos. Se demuestra que la organización perceptual, sobre la cual se basa la selección atencional, se logra por la acción de procesos guiados por las características físicas de los estímulos y procesos determinados por el conocimiento previo de los sujetos. Se demuestra también que el tránsito de la atención de un aspecto a otro de la escena es lento, lo cual se corresponde más con un procesamiento en paralelo que con un procesamiento en serie. Se demuestra además, mediante el registro de la actividad eléctrica cerebral, que la selección atencional basada en objetos también actúa en las primeras etapas de la vía visual.

Este conjunto de resultados obliga, al menos, a una profunda revisión del modelo teórico dominante, y en nuestro criterio, a la necesidad de su sustitución. Los métodos desarrollados además de un interés teórico, tienen aplicaciones en la clínica.

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La complejidad perceptual del mundo

El hombre está inmerso en un ambiente complejo que lo enfrenta en cada momento a una infinidad de estímulos sensoriales. Los estímulos que lo rodean no tienen ni la misma intensidad, ni la misma importancia en función de los objetivos de cada actividad. Es imprescindible entonces extraer, de entre todas las informaciones disponibles, aquella o aquellas que sean relevantes para lograr un comportamiento funcional en el medio. La selección de los estímulos sensoriales (o entradas de información) relevantes, para su procesamiento ulterior, se alcanza o partiendo de la prominencia y organización de sus atributos (proceso guiado por los estímulos, es decir 'de abajo-a-arriba'), o partiendo de los objetivos, necesidades, expectativas y conocimientos previos del sujeto (proceso guiado por las metas, es decir 'de arriba-a-abajo'). También es posible una combinación de ambas estrategias.

Concepto de atención

La atención se concibe como la vía de acceso de la información al procesamiento ulterior. En otras palabras, actuaría como una llave de paso para los estímulos en su camino hacia el acceso a memoria, al control de la conducta, o la entrada a la conciencia. La atención sería el proceso encargado de la regulación de la experiencia perceptual. La atención es responsable de la selectividad del procesamiento sensorial, permitiendo a unos estímulos recibir un tratamiento preferencial sobre otros (siendo detectados y discriminados con mayor rapidez y precisión, y registrados más vívidamente en la conciencia y en la memoria), y además ejercer una mayor influencia sobre la conducta.

Los estudios clásicos de la atención concibieron la selección como un proceso de filtraje, postulando estructuras que determinan un cuello de botella en el flujo de la información. Esto determina la necesidad de eliminar parte de la información sensorial, lo cual puede asemejarse a la acción de un filtro (Broadbent, 1958; Deutsch y Deutsch, 1963; Treisman, 1964). También se postuló otro tipo de modelo, de administración de recursos, que supone la existencia de una capacidad atencional limitada que debe ser adecuadamente distribuida entre diferentes tareas (Kahneman, 1973; Navon y Gopher, 1979). Estos enfoques comparten la idea de que los estímulos compiten entre sí (bien sea por estructuras o recursos) y se interfieren unos a otros.

Estos tipos de modelos clásicos resultaron metáforas útiles que estimularon la investigación, pero poseían relativamente poco contacto con las investigaciones neurofisiológicas. No dejaban claro cuál era la base neural ni del cuello de botella, ni del recurso limitado.

El sistema visual

El estudio de la atención en la vía visual se ha convertido en un tema de gran actualidad. Por el gran volumen acumulado de datos psicofísicos, anatómicos, neuropsicológicos y fisiológicos sobre la vía visual, así como por la existencia de modelos animales con funciones visuales muy similares al hombre (los monos), la atención visual pudiera ser la primera de las funciones mentales complejas cuya base neural se pudiera comprender. Las neurociencias cognitivas han establecido en las ultimas décadas que los estímulos visuales son procesados en el sistema nervioso en forma de múltiples tipos de representación mental, las cuales se corresponden con diferentes formas de codificación de la actividad neural. Estudios con métodos de neuroimágenes (como la tomografía de emisión de positrones o la resonancia magnética funcional) han identificado numerosas áreas de la corteza cerebral que actúan representando distintos aspectos de una escena visual. Estudios con microelectrodos en monos han identificado diversas poblaciones neuronales, cada una capaz de codificar para zonas restringidas del campo visual (campos receptivos) atributos altamente específicos (color, forma, dirección del movimiento etc.).

La información recogida en la retina se envía, a través del núcleo talámico geniculado-lateral, a la corteza visual primaria (o área V1). Las múltiples cortezas visuales (más de 25 en los primates) están organizadas en varias rutas paralelas, donde cada área envía información a una superior. Las representaciones creadas en las estaciones más elevadas de cada ruta son más complejas y especializadas que las de estaciones inferiores. Casi todas las áreas corticales implicadas en la visión están organizadas retinotópicamente, lo que significa que cada una contiene un mapa topográfico completo del campo visual.

Se reconocen dos rutas principales de procesamiento. La vía ventral empieza en V1 y se dirige hacia la corteza infero-temporal, involucrando áreas como V4. Esta vía se especializa en atributos como la forma y el color, siendo relativamente insensible al movimiento y la localización del estímulo. Se considera que participa en el reconocimiento de los objetos, por lo cual se conoce como la ruta del ´QUÉ´. La ruta dorsal empieza también en V1 y se dirige hacia el lóbulo parietal posterior, involucrando áreas como V5. Esta vía se especializa en el análisis del movimiento y la localización, siendo relativamente insensible al color y la forma, y quizás funcionando para dirigir la manipulación o acción sobre objetos. Por eso se le conoce como la ruta del ´DÓNDE´ o la ruta del ´CÓMO´. Las lesiones de la ruta dorsal tienen efectos dramáticos sobre el control de la atención visual, por lo que se debate el peso relativo que tienen ambas vías en la atención visual.

¿Qué tipo de representación mental se selecciona por la atención visual?

Hemos visto que se crean representaciones diversas de una escena dentro del sistema visual, desde sencillas hasta complejas, algunas enfatizando la localización y el movimiento y otras la forma y el color. La selección atencional debe operar sobre algunas de estas representaciones, pero la pregunta es: ¿sobre cuáles?

En los últimos años han pugnado dos respuestas rivales a esta pregunta. Por un lado, modelos que postulan una selección espacial (es decir, la atención se dirige hacia una localización específica de la escena visual), y por el otro, modelos que postulan que la atención se orienta a los objetos (es decir, se selecciona un objeto perceptual derivado de la organización previa de la escena). Esto implica dos mecanismos neurales distintos.

Los modelos espaciales se apoyan en el hallazgo fisiológico de que las áreas de la corteza cerebral implicadas en la visión están organizadas retinotópicamente. Los modelos espaciales más conocidos proponen que la atención selecciona regiones determinadas del campo visual en esos mapas. Para estos modelos las representaciones se seleccionan sobre la base de su localización dentro de un sistema de coordenadas espaciales geométricas, es decir, un criterio topográfico y geométrico determina qué es seleccionado. Este tipo de selección podría actuar desde las primeras áreas visuales, ya que la organización retinotópica está presente en todas ellas.

Una metáfora espacial clásica es la de un foco atencional que actúa como una linterna, iluminando regiones del campo visual (Posner, 1978, 1980). Toda la información comprendida en la región espacial hacia la cual se dirige el foco se procesa prioritariamente (zona iluminada) en comparación con la que se encuentra fuera de dicha región (zona de penumbra). Esta metáfora concuerda con muchas observaciones sobre la atención. El foco, como el haz de luz de la linterna, se concibe como unitario, convexo y compacto, y se podría desplazar serial y rápidamente de un sitio a otro a través del espacio geométrico. Otro elemento que se incorpora frecuentemente a los modelos espaciales (Treisman, 1988) es la idea de que la atención permite la integración de los rasgos elementales correspondientes a una localización en el campo visual (los cuales están representados en distintas áreas corticales) dentro de una representación más compleja correspondiente a un objeto (que sería, por tanto, consecuencia de la atención).

Últimamente la perspectiva espacial se ha flexibilizado, admitiendo formas del foco que se adaptan a la organización perceptual de la escena (Vecera y Farah, 1994; Vecera, 1994; Kramer, Weber y Watson, 1997; Wolfe, Cave y Franzel, 1989), pero siempre reservándole al espacio el papel protagónico en la selección. Los modelos espaciales, clásicos o modificados, son hegemónicos hasta hoy, existiendo no sólo datos psicofísicos en su favor, sino evidencias clínicas y psicofisiológicas que los confirman.

Entre las evidencias a favor de la selección espacial, existen numerosos estudios con Potenciales Relacionados con Eventos (PRE) registrados en el cuero cabelludo de sujetos experimentales humanos, según los cuales las señales eléctricas cerebrales provocadas por estímulos presentados en localizaciones espaciales atendidas tiene una mayor amplitud que aquellas presentadas en localizaciones espaciales no atendidas (Mangun y Hillyard, 1991, 1995; Luck y cols., 1994; Hillyard y Anllo-Vento, 1998). Tanto la latencia de estas señales (una de ellas tan temprana como 80 milisegundos después del estímulo), como estudios de localización del origen de las mismas que las ubican en V4 (Clark y Hillyard, 1996), indican que la atención espacial está afectando procesos perceptuales muy tempranos en la visión. Este efecto estaría localizado sobre las áreas extraestriadas tempranas, inmediatamente después de actuar la corteza primaria o V1. Este efecto es consistente con la atención como un filtro que atenúa señales.

La atención orientada a objetos perceptuales consistiría en una selección entre representaciones más complejas que integran varios rasgos o atributos elementales, lo que implica que primero se organiza perceptualmente la escena en objetos, y después se selecciona uno de ellos. Aquí la atención es subsiguiente a la formación de una representación de objeto. La organización de la escena ocurre debido a procesos de segmentación e integración, segregación figura-fondo, y los otros principios de la Gestalt, que producen una imagen organizada en representaciones de un orden superior (objetos), cada una integrando varios rasgos o atributos elementales.

Los modelos de la atención orientada a los objetos (Duncan, 1984, 1995; Baylis y Driver, 1993; Lavie y Driver, 1996; Egly, Driver y Rafal, 1994; Behrmann, Zemel y

Mozer, 1998; Duncan y Humphreys, 1989, 1992; Nakayama, He y Shimojo, 1995) postulan que la atención selecciona un objeto para procesarlo con prioridad. Todos los atributos del objeto seleccionado son igualmente procesados, al tiempo que dos objetos diferentes se interfieren, compiten entre sí. Esta teoría se apoya en una concepción fisiológica que plantea la competencia integrada de los campos receptivos de las neuronas, es decir, la excitación conjunta de aquellas neuronas que procesan atributos de un mismo objeto, y su competencia con (inhibición de) aquellas otras que procesan atributos de otro objeto. Si bien hay evidencias psicofísicas a favor de este enfoque, al comenzarse este trabajo de tesis no existían evidencias psicofisiológicas, con PRE por ejemplo, a favor del mismo.

Es difícil disociar los efectos debidos a la selección entre localizaciones espaciales de aquellos debidos a la selección entre objetos, pues los objetos siempre ocupan un lugar particular en el espacio. El espacio es uno de los atributos de los objetos, y podríamos decir que en la mayoría de los escenarios naturales se convierte en un atributo esencial: un mismo objeto no puede estar en dos lugares simultáneamente, al tiempo que objetos diferentes ocupan sitios diferentes.

Los partidarios de los modelos basados en la organización perceptual no espacial de la escena visual han utilizado tres vías fundamentales para desvincular la selección espacial de la orientada a objetos: 1- presentación de objetos superpuestos en una misma región del espacio, 2- seguimiento de objetos en movimiento desvinculados de cualquier localización espacial fija, y 3- contraposición del agrupamiento perceptual a la proximidad espacial, es decir, ver el efecto facilitador que produce sobre el procesamiento de dos estímulos el hecho de que pertenezcan a un mismo conjunto perceptual, más allá de la distancia que exista entre ellos. Los resultados psicofísicos obtenidos con estos métodos no constituyen evidencias inequívocas en favor de la atención orientada a los objetos, pues pueden explicarse mediante enfoques alternativos, ya sea a través de modelos espaciales modificados, o por selecciones basadas en otros rasgos elementales como el color, el contenido de frecuencia espacial, el movimiento, etc.

Hoy en día muchos aceptan que ambos tipos de selección pueden coexistir. Pero a menudo se sugiere que la selección atencional de un objeto ocurre en estadios más tardíos del procesamiento que la selección espacial, es decir en áreas de integración de la vía visual posteriores al procesamiento de los rasgos elementales. Por tanto, según este punto de vista, la selección espacial podría operar sobre áreas visuales de bajo nivel (anteriores anatómica, funcional, y temporalmente) mientras que la selección de objetos podría operar sobre áreas superiores. Sin embargo no hay evidencias claras a favor de esta idea.

Los autores que defienden una selección atencional orientada a los objetos han utilizado diseños en los cuales se organiza perceptualmente la escena a partir de procesos guiados por las características físicas de los estímulos, estudiando la selección de objetos artificiales construidos a partir de la conjunción de sus atributos elementales. Es importante destacar que en la organización perceptual de una escena visual también intervienen procesos de arriba-a-abajo, cuya contribución merece ser estudiada.

Un ejemplo claro de lo anterior sería el procesamiento de los rostros humanos. Si bien es cierto que un rostro puede ser tratado como un objeto, en función de la integración de una serie de atributos elementales que lo componen (forma, color, textura, etc.), vale destacar que es un objeto tan familiar que puede ser reconocido como tal, en función del conocimiento previo que poseemos acerca de su estructura básica (relación entre los rasgos que lo componen, por ej.: posición relativa de la boca y los ojos). Esta estructura básica está tan sobreaprendida en la experiencia de los seres humanos, que se conoce que manipulaciones tales como la inversión del rostro alteran (retardan) seriamente cualquier procesamiento del mismo.

La atención en el tiempo

La atención no puede quedar atrapada en una sola fuente de información. Un ejemplo de lo catastrófico que sería esto es el síndrome de Balint, donde el paciente sólo puede ver un objeto a la vez, en el cual queda atrapada su atención (simultagnosia). Si estos pacientes observan el rostro de alguien que tiene unas gafas puestas, sólo pueden ver el rostro o las gafas pero no ambos. La atención debe cambiar de una representación a otra en el tiempo. ¿Pero cuán rápido puede hacerse este cambio? Éste es un segundo punto de debate.

Algunos sostienen que la atención se puede desplazar rápidamente de un sitio espacial a otro, dedicándole sólo decenas de milisegundos a cada uno. Otros sostienen que la atención demora hasta cerca de medio segundo en cambiar de objeto. Parte del debate puede deberse a problemas metodológicos de cómo se mide la duración del tránsito de la atención.

La primera posición se basa en los experimentos de búsqueda visual (Wolfe, 1998), en los cuáles debe buscarse un estímulo "diana" entre distractores, todos presentados simultáneamente. En algunas condiciones que demandan atención, el tiempo medio de búsqueda antes de responder si está presente o no la diana, crece con el número de distractores. Se ha utilizado la pendiente de la curva que relaciona el tiempo de reacción con el número de distractores como un estimado de la velocidad con la cual el foco atencional se desplaza serialmente de elemento en elemento de la escena. Este estimado es de alrededor de 30 milisegundos. Sin embargo, este enfoque ha sido criticado porque la presentación simultánea de los estímulos no garantiza el carácter serial del procesamiento.

Por otra parte, los que plantean un tránsito lento de la atención, se basan en variantes experimentales que presentan los estímulos de forma secuencial y rápida. En una primera variante (Duncan, Ward y Shapiro, 1994; Ward, Duncan, y Shapiro, 1996), dos estímulos son presentados (y rápidamente enmascarados) con un intervalo de tiempo variable entre la presentación de ambos. El procesamiento del primer estímulo interfiere el del segundo para los intervalos más cortos. Esto se conoce como 'tiempo de estacionamiento atencional', pues se plantea que se debe a que la atención permanece atrapada por el primer estímulo.

Una segunda variante utiliza la presentación visual serial y muy rápida (PVSR) de estímulos "diana" mezclados entre distractores (más de 10 estímulos por segundo), generalmente en una misma localización espacial (Raymond, Shapiro y Arnell, 1992; Shapiro, Raymond y Arnell, 1994). Uno de los fenómenos descritos a partir de este diseño es el 'parpadeo atencional', consistente en una incapacidad para percibir un segundo estímulo "diana" breve tiempo después de la presentación de uno anterior. Otro fenómeno descrito es la 'ceguera ante estímulos repetidos', consistente en una incapacidad para percibir o recordar el segundo de dos estímulos iguales, presentado breve tiempo después del primero. Tanto el 'tiempo de estacionamiento atencional' como el 'parpadeo atencional' tardan varios cientos de milisegundos. La duración de la 'ceguera ante estímulos repetidos' es algo menor. No quedan claras las causas de estos efectos en el tiempo, ni cuáles (si es que alguno) son equivalentes entre sí.

Papel de los eventos

Casi todos los estudios de la atención visual se han realizado con estímulos que aparecen y desaparecen de improviso sobre la pantalla de un monitor de computadora. La aparición o desaparición brusca de un objeto no es frecuente en la vida real (salvo excepciones tales como una tormenta de relámpagos o el destello de luces en una discoteca). Es mucho más frecuente la percepción de modificaciones en los objetos preexistentes en la escena visual. Por ejemplo, cuando observamos el rostro de un interlocutor, percibimos los cambios de dirección de su mirada, los movimientos de sus labios al hablar, la variación de los rasgos y gestos que denotan sus expresiones emocionales, etc. Otro ejemplo podría consistir en que cuando conducimos un automóvil, percibimos los cambios en la trayectoria, la velocidad y la distancia de los otros autos, así como los desplazamientos de los transeúntes, y los cambios de luces en los semáforos, entre otros eventos.

Muchos de los estudios sobre atención visual utilizan como método la presentación visual serial y rápida (PVSR). En este método, las características que deben detectarse o discriminarse en un estímulo determinado están presentes durante todo el tiempo de duración del estímulo, y el tiempo de vida de cada estímulo es breve, sustituyéndose unos a los otros. En esta tesis proponemos la utilización del método de las Transformaciones Seriales Rápidas de Objetos (TSRO). En este método deben discriminarse eventos breves que modifican, sucesiva y rápidamente, objetos preexistentes y estables en el campo visual.

Nuestro método es ventajoso en varios sentidos: En primer lugar, como ya vimos, es mucho más natural que los objetos cambien, se transformen, antes que aparezcan y desaparezcan sustituyéndose unos a otros. En segundo lugar, y más allá del valor ecológico, los objetos que se presentan abruptamente pueden capturar automáticamente la atención. En tercer lugar, variando el tiempo existente entre los eventos, es posible estudiar la dinámica temporal de la atención, es decir, los cambios que se producen en el estatus atencional de los objetos a través del tiempo.

Resumen de Problemas

Existe un modelo hegemónico en la comprensión de la atención visual. Según este modelo, la selección se basa en la acción de un foco unitario (linterna) que se dirige hacia una región determinada del campo visual, priorizando el procesamiento de la información contenida en dicha zona. El foco atencional es capaz de desplazarse serial y rápidamente de un sitio a otro del espacio. Se propone, además, que esta selección basada en el espacio es anterior a otros posibles mecanismos de selección, y se privilegia como la única cuyas bases neurales se localizan en las primeras áreas de la corteza visual extraestriada.

A pesar de la acumulación de numerosos datos experimentales incompatibles con este modelo clásico, las cuales han estimulado posiciones teóricas alternativas, hay un número de problemas sin solucionar. Por una parte, no existen demostraciones inequívocas de la selección atencional basada en objetos, siendo posible explicar los resultados de experimentos realizados con este fin a partir de mecanismos de selección alternativos. Además, existen discrepancias en los estimados del tiempo que demora la atención para cambiar de un estímulo a otro. Por otra parte, cuando se acepta la atención basada en objetos se supone, sin evidencias claras, que actúa a través de mecanismos relativamente tardíos. Otra limitación radica en que escasean los estudios sobre las bases fisiológicas de la atención dirigida a objetos. Finalmente, a pesar de su importancia ecológica y metodológica, prácticamente no se ha estudiado cómo la atención se dirige a eventos que modifican objetos preexistentes en una escena.

Hipótesis

En contraposición al modelo hegemónico de la selección espacial, pensamos que la distribución de la atención visual es dirigida por la organización perceptual de la escena, derivada ésta de procesos perceptuales tales como la segmentación e integración de las imágenes o la segregación figura-fondo, y en los cuales intervienen condiciones de 'abajo-a-arriba' (impuestas por las características físicas de los estímulos) y condiciones de 'arriba-a-abajo' (determinadas por las metas). Esta influencia también involucra mecanismos neurales muy tempranos en la vía visual.

Objetivo general

Demostrar que la efectividad y el curso temporal de la atención a los eventos que ocurren en una escena visual está determinada por la organización perceptual de la misma, y no exclusivamente por factores espaciales como es generalmente aceptado, así como esclarecer los mecanismos neurales de esta selección basada en objetos.

Objetivos específicos

1. Evaluar si la atención selectiva a eventos se basa en la segmentación de la escena visual en objetos, tanto o más que en los factores espaciales, descartando la participación de mecanismos alternativos, tanto espaciales como de filtraje sensorial de bajo nivel.

2. Describir la dinámica temporal de la atención a eventos (tiempo mínimo para que la atención cambie entre eventos), estudiando la influencia de factores espaciales y de la organización perceptual de la escena.

3. Determinar (con técnicas electrofisiológicas y psicofísicas) cuán temprano en la vía visual ocurre la selección atencional de eventos basada en objetos.

Novedad del trabajo

Esta tesis aborda una temática de gran interés en la psicología y neurociencias actuales, la atención visual. Hasta hace poco se consideraba la influencia del espacio en la escena visual como el elemento primario en el control de dicho proceso mental. Antes de la publicación de los artículos contenidos en la tesis, no se había demostrado electrofisiológicamente la atención visual basada en objetos, lo cual probablemente se debía a dificultades con el diseño de los estímulos. Si bien existían algunas evidencias piscofísicas en favor de la atención selectiva basada en objetos, éstas eran criticadas y se proponían explicaciones alternativas a las mismas. Tampoco se había medido la duración del tránsito atencional entre sitios de un mismo objeto. Las innovaciones metodológicas contenidas en la tesis permitieron, por primera vez, encontrar los signos electrofisiológicos, rechazar las explicaciones alternativas, y medir la duración del tránsito atencional antes mencionados, todo lo cual obliga a revisar la teoría.

El contenido de la tesis se ha publicado en revistas internacionales de alto prestigio (J. Exp. Psychol. ; Cognition; J.Cog. Neurosci.; Brain & Cognition; Vision Res), lo que avala su aceptación por la comunidad científica internacional. Uno de los trabajos de la serie ha sido citado 14 veces (entre 1999-2000) en artículos escritos por autoridades mundiales. Las citas aparecen en revistas internacionales de muy alto impacto (Trends in Cognitive Science; Nature; Nature Neuroscience; J. Neuroscience, Clinical Neurophysiology; Current Opinion en Neurobiology; Brain, Philosophical Transactions of the Royal Society; Behaviorial & Brain Science; J. Exp. Psychol.). Fue citado en tres revisiones independientes de 'Current Opinion in Neurobiology' como artículo muy destacado en el año. Además, fue descrito en detalle en el capítulo sobre el tema de la atención en la Encyclopedia of the Human Brain (Academic Press). Lo mismo sucedió en un capítulo de un libro publicado por la Oxford University Press. Por último, el conjunto de este trabajo obtuvo el premio anual de la Academia de Ciencias de Cuba en 1998, y el premio especial del CITMA al trabajo científico de mayor originalidad del país en ese año.

Revisión Bibliográfica

Inicialmente serán abordados de forma general dos aspectos estrechamente vinculados con la atención visual: la organización anátomo-fisiológica del sistema visual, su sustrato biológico, así como la percepción visual, proceso sobre el cual opera.

Organización anátomo-fisiológica del sistema visual

El sistema visual es el responsable de la transducción de la energía luminosa en actividad neural. El encéfalo procesa la información básica que recibe desde el ojo sobre la distribución espacial de varias longitudes de onda luminosas. Diferentes tipos de procesamiento sobre la misma entrada de información nos permiten tomar decisiones sobre el color, la posición, la forma, la profundidad, el movimiento de los estímulos visuales.

Anatómicamente, la vía parte desde el ojo, una elaborada estructura que funciona como un sistema de lentes que enfocan la luz sobre sobre su superficie interior, la retina, donde se produce la primera etapa del procesamiento visual. En la retina se encuentran los auténticos elementos receptores: bastones y conos, los cuales se conectan con las células bipolares, que a su vez realizan sinapsis con las células ganglionares, cuyos axones en conjunto forman el nervio óptico. Entre los elementos receptores y las células ganglionares se produce una enorme convergencia de información; las células horizontales y las amacrinas establecen las conexiones laterales, siendo especialmente relevantes en las interacciones inhibitorias al interior del circuito retiniano (Rosenzweig y Leiman, 1992).

Ambos nervios ópticos confluyen en el quiasma óptico, donde se entrecruza la información: en cada nervio óptico los axones provenientes de la retina nasal atraviesan hacia el lado opuesto del encéfalo, en tanto los provenientes de la retina temporal se proyectan ipsilateralmente. Una vez abandonado el quiasma óptico (entrecruzada la información) el conjunto de los axones de las células ganglionares conforma el tracto óptico. Cada tracto óptico (conformado por axones provenientes de ambos ojos) conduce en lo adelante la información correspondiente al hemicampo visual contralateral, y la proyecta fundamentalmente en el núcleo geniculado lateral del tálamo. Los axones de las células postsinápticas del núcleo geniculado lateral constituyen las radiaciones ópticas, las cuales terminan sobre las áreas primarias de la corteza visual en la región occipital, que se conectan luego con el resto de las áreas visuales que procesan diversas modalidades (Rosenzweig y Leiman, 1992).

Funcionalmente, desde el mismo inicio de la vía existen dos sistemas diferentes que se corresponden con las distintas poblaciones de receptores en la retina: El sistema fototópico, formado por los conos, concentrados fundamentalmente en la fóvea y sensibles al color, está especializado en la visión diurna al ser sensible a altos niveles de intensidad luminosa; el sistema escotópico, formado por los bastones, más periférico y especializado en la visión nocturna, pues es sensible a bajos niveles de luminosidad. El primero de ambos sistemas se caracteriza porque sus campos receptivos son más pequeños y necesitan un menor tiempo de integración de la información, sacrificando sensibilidad en función de ganar en poder de discriminación, por lo que, además, interviene en la percepción de la forma (detalles finos) (Kandel, Schwartz, y Jessell, 1991).

La extraordinaria sensibilidad de conos y bastones está determinada por sus características estructurales y bioquímicas, aumentando la probabilidad de que los quantos de luz sean capturados por fotopigmentos especiales cuya estructura química cambia de forma ante la incidencia de la luz, iniciando una cascada de fenómenos que culmina en el potencial generador que provoca la señal eléctrica inicial de activación de la vía visual.

El sistema de proyección retiniana también guarda cierto paralelismo, pues las células ganglionares pueden ser clasificadas como M o P en función de sus características funcionales. Las ganglionares M, alguna de las cuales son insensibles al color, poseen campos receptivos grandes y respuestas fásicas, activándose mejor ante estímulos de baja frecuencia espacial; en tanto las ganglionares P, sensibles espectralmente, presentan campos receptivos pequeños y respuestas tónicas, activándose con contenidos de frecuencia espacial alta. Ambos tipos de células se proyectan mayoritariamente hacia capas diferentes del núcleo geniculado lateral: las M hacia las dos capas ventrales (magnocelulares) y las P hacia las cuatro dorsales (parvocelulares), conservando la segregación. Las células de ambos sistemas (magno y parvocelular) mantienen propiedades semejantes a las ganglionares M y P respectivamente (Kandel, Schwartz, y Jessell, 1991).

El sistema magnocelular continúa proyectándose hacia la corteza occipital sobre las áreas visuales V1 (estriada), V2, V3, V5 (MT), y 7a, constituyendo la vía dorsal hacia la región parietal posteriol (llamada "vía del dónde"), implicada principalmente en el procesamiento del espacio, la profundidad y el movimiento. El sistema parvocelular, por su parte, se proyecta hacia las áreas V1, V2, V4, e inferotemporeal (IT), constituyendo hacia el lóbulo temporal la vía ventral (llamada "vía del qué"), implicada principalmente en el procesamiento de la forma y los contornos y el color. La segregación de ambas vías es más bien esquemática pues, dados los procesos de convergencia y divergencia típicos del sistema nervioso, existen numerosas conexiones recíprocas, tanto subcorticales como corticales, ascendentes y descendentes (Kandel, Schwartz, y Jessell, 1991).

A medida que ascendemos en el sistema visual, encontramos niveles más complejos y especializados, de mayor integración de procesamiento. Los campos receptivos de las neuronas, de nivel en nivel, se hacen mayores y responden a rasgos más específicos. Las imágenes visuales complejas son construidas en centros de procesamiento sucesivamente superiores desde las entradas provenientes de las vías paralelas que procesan las distintas modalidades. Esta jerarquización se observa para todas las modalidades del procesamiento visual: forma, color, localización, movimiento, etc.

Considerando, por ejemplo, el procesamiento de la forma, se observa que tanto las células ganglionares como las del núcleo geniculado lateral poseen campos receptivos concéntricos, con centro y periferia antagónicos, que responden a puntos luminosos. Las células simples de la corteza visual primaria responden a estímulos más específicos, tales como líneas, con una posición y orientación determinadas. Las células complejas no precisan de una posición particular, en tanto las hipercomplejas responden a ángulos y bordes. Hacia los finales de la vía, se plantea la existencia de células con campos receptivos siempre foveales y muy grandes, capaces de responder sólo ante patrones complejos como una cara o una mano (Rosenzweig y Leiman, 1992).

Por otra parte, cada nivel sucesivo del sistema visual constituye un mapa detallado del mundo visible. La retina recibe una imagen bastante exacta del campo visual, luego envía señales a los núcleos visuales del diencéfalo y el mesencéfalo que conservan la disposición espacial. La información visual finalmente llega a las diversas áreas de la corteza visual, de procesamiento específico, que costituyen mapas topográficamente ordenados de la superficie receptora, los cuales reflejan mejor la agudeza de las discriminaciones espaciales que las proporciones reales (la fóvea se encuentra más representada).

Por último, la corteza visual primaria presenta una organización columnar.

Dentro de una zona concreta correspondiente a una determinada región del campo visual, existen bandas separadas de células que representan el campo visual de los ojos ipsi y contralateral (bandas de dominancia ocular). En el interior de estas bandas hay columnas de neuronas en los que sus campos receptivos son selectivos para estímulos de una misma orientación angular (sintonía). Las columnas adyacentes son selectivas a orientaciones similares, recorriéndose en una macrocolumna, de forma gradual y ordenada, todas las orientaciones posibles. Al interior de las bandas, interrumpiendo la progresión de las columnas de orientación, aparecen las manchas o estacas, formadas por células vinculadas al procesamiento del color (células de doble oponencia). Estas estacas son más abundantes en aquellas regiones corticales que representan la fóvea, donde existe una mayor concentración de conos (Kandel, Schwartz, y Jessell, 1991; Rosenzweig y Leiman, 1992).

Percepción visual

Inicialmente la percepción fue concebida como una simple integración de sensaciones, en este caso visuales, basada en operaciones analítico-sintéticas que descomponían y recomponían la imagen a partir de sus atributos sensoriales más elementales. Esta perspectiva tenía como base la idea de que el ojo humano, y el sistema visual en general, funcionaban de forma análoga a una cámara fotográfica que, de manera mecánica, reproducía una copia fiel de la realidad.

Actualmente se plantea que los estímulos sensoriales son codificados en el sistema nervioso a través de patrones específicos de actividad neural, originando las correspondientes representaciones mentales sobre las cuales el sistema cognitivo opera (Kandel, Schwartz, y Jessell, 1991). El carácter reflejo de la percepción visual, característico de todo contenido o proceso psíquico, no implica una reproducción mimética y pasiva de los estímulos físicos, sino un proceso activo y transformativo en el que, al mismo tiempo, no se representan todos los estímulos presentes y se incorporan aspectos inexistentes.

Percibir es una acción cíclica en que se combinan las entradas de información con los esquemas cognitivos y las expectativas del sujeto, es un proceso constructivo en el que el sujeto elabora un esquema anticipatorio que guía la entrada de la información. Por tanto, la percepción visual, como todos los procesos cognitivos, se mueve en dos direcciones: de Abajo-a-arriba, es decir, guiada por las características propias de los estímulos (intensidad, tamaño, contraste, repetición, movimiento, novedad, etc.), y de Arriba-a-abajo, guiada por los procesos superiores (motivaciones, intereses, expectativas, experiencia previa, disposición, etc.).

Una derivación de lo anterior, de gran relevancia para el desarrollo ulterior de esta investigación, es el hecho de que el mundo no es percibido como un conjunto de atributos perceptivos (cualidades percibidas de un estímulo). La percepción se estructura en unidades psíquicas coherentes, se organiza en configuraciones significativas, deviniendo en el proceso de discriminar entre los estímulos e interpretar sus significados más allá de su simple detección (Weintaub y Walker, 1966).

La organización perceptual de una escena visual compleja se basa en una serie de procesos que operan generalmente de manera simultánea, apoyándose unos a los otros (Palmer y Rock, 1994). Entre esos procesos se encuentran fundamentalmente el agrupamiento perceptual, la segregación figura-fondo, la percepción de los contornos, y el completamiento de imágenes realmente discontinuas.

El primero de estos procesos, el agrupamiento perceptual, ha sido bien estudiado desde etapas tempranas de la psicología (fundamentalmente por la escuela de la Gestalt), y consiste en la tendencia a percibir como un conjunto orgánico a aquellos elementos que se relacionen entre sí en base a algún criterio de similitud (Gillan, 1987), bien sea porque se encuentren próximos espacialmente, porque sean semejantes, compongan alguna simetría, establezcan una continuidad, o se muevan en una misma dirección.

La segregación de figura-fondo se basa en la segmentación de la imagen en una figura, que adquiere forma y significado propios emergiendo por delante en un plano subjetivo, y un fondo informe y sin significado que se percibe como si estuviera completo por detrás de la figura (Bartley, 1969). Un fenómeno interesante que opera en este proceso es la percepción bi-estable, que ocurre cuando la segregación de figura y fondo es reversible, es decir, lo que antes fue figura puede percibirse como fondo y viceversa, siendo ambos estados perceptuales equiprobables.

La percepción de los contornos o bordes consiste en la percepción de cambios bruscos de brillo o color que proporcionan la forma a una determinada figura. El completamiento, por su parte, es la tendencia a percibir como figuras continuas lo que en la realidad se presenta como partes separadas, bien sea por oclusiones (completamiento modal), o por la percepción de contornos ilusorios (Grossberg y Mingolla, 1987) que dan lugar a una buena forma (completamiento amodal).

Por último, a los fines de este trabajo cabe destacar la existencia de un fenómeno perceptual interesante: la constancia perceptiva, que no es más que la estabilidad de los objetos percibidos, cuya representación mental continúa idéntica en cuanto a forma, tamaño, brillo, y color, aún cuando la imagen retiniana varíe en dependencia de la variación de los ángulos visuales, la distancia o las fuentes de luz (Kandel, Schwartz, y Jessell, 1991). Este mecanismo es un útil instrumento (e indicador) de la generalización y abstracción en el proceso perceptual.

La atención: esbozo de los enfoques experimentales cognitivos clásicos

"Todos saben qué es la atención. Es la toma de posesión por la mente, de forma vívida y clara, de uno de los numerosos posibles objetos simultáneos o corrientes de pensamiento." (James, 1890)

Sin pretender hacer historia, vale señalar que el tema de la atención como fenómeno, proceso o función psicológica fue introducido por los principales autores (Wundt, Titchener, James, Kulpe, Catell, etc.) desde la aparición misma de la Psicología como ciencia independiente. Los conceptos de atención propuestos por estos autores están estrechamente vinculados al significado que la psicología de sentido común le adjudica al término, pero tienen el valor de delinear sus aspectos fundamentales y abordarlos con cientificidad (la de la época, claro está), combinando la introspección con algunas formas de experimentación formal.

Considerando el tema más específicamente desde la perspectiva del procesamiento de la información, se puede plantear que el flujo de información que nos rodea desborda no sólo la capacidad limitada de entrada al sistema sino, y fundamentalmente, su capacidad de procesamiento. Los mecanismos, estructuras y procesos vinculados a las estrategias utilizadas por el sistema para dar solución satisfactoria a tales limitaciones, han dado lugar a numerosas y diferentes aproximaciones al tema, y al concepto, de la atención como proceso mental.

Una de las formas en que se ha concebido la atención es asimilándola a conciencia o vigilia, a partir de la dicotomía entre procesos controlados y procesos automáticos (Shiffrin y Schneider, 1977; Logan, 1978; 1979). En este caso la atención interviene como focalizador de la conciencia sobre aquellos conjuntos de actos y operaciones que sólo pueden realizarse bajo el seguimiento activo del sujeto, en contraposición con aquellos otros que no lo requieren. A medio camino en este continuum se encuentran los procesos semiautomáticos, menos demandantes de atención. Incluso los procesos mecanizados se automatizan a través de un proceso de interiorización en el cual sí interviene la atención.

La atención también se ha trabajado con un enfoque estructural. Se ha pensado como el mecanismo o la estructura que selecciona cuál información entra al sistema y cuál no. Esta metáfora del 'filtro' atencional se ha desarrollado con diversos modelos y diseños experimentales en dependencia de dos aspectos fundamentales: el temporal, es decir, el momento en el cual se produce el cuello de botella informacional y el filtraje (filtros tempranos o sensoriales -Broadbent, 1958-, y tardíos o poscategoriales - Deutsch y Deutsch, 1963; Norman, 1968-); y el de la cualidad del filtro, es decir, si la información rechazada no se procesa en absoluto dejando libre el canal a la información atendida o si, por el contrario, sólo es atenuada (Treisman, 1964). Ambos aspectos están asociados también al nivel, la complejidad, la profundidad de procesamiento al que se somete la información. Este enfoque ha dado lugar al concepto de *atención selectiva.*

Otra forma de acercarse al tema atencional proviene de los modelos económicos de administración de recursos. Estos modelos de capacidad limitada (Kahneman, 1973) postulan que la atención es un recurso finito del cual dispone el procesador central (PC) del sistema para enfrentar las diferentes demandas. El PC funciona como un administrador que evalúa las necesidades atencionales de cada tarea a ejecutar y les asigna los recursos estratégicamente en función de la disponibilidad y de la jerarquía de tareas. Este enfoque económico ha desarrollado diversos modelos y diseños experimentales en función de si los recursos son generales o específicos para (Navon y Gopher, 1979) cada tarea. Esta aproximación origina el concepto de *atención dividida*, relacionado con el número y el tipo de tareas que pueden realizarse simultáneamente.

Una cuarta variante aproximativa, a medio camino entre los modelos estructurales o de filtro y los modelos procesuales o de capacidad, se centra en los analizadores o discriminadores. Tales analizadores o discriminadores no son sino estructuras que intervienen en la ejecución de las tareas, y cuya utilización debe ser compartida proporcionalmente al grado de similitud entre las tareas a realizar: Dos tareas de una misma modalidad demandan el uso de una misma estructura mucho más que otras dos de modalidades diferentes. Una de las mayores inconsistencias de este enfoque es que al menos teóricamente puede considerarse una tipología infinita de analizadores diferentes, casi tantos como tareas posibles.

Más allá de todas estas perspectivas es posible extraer algunos elementos comunes que definirían los rasgos más importantes en una definición integradora de la atención. En mi opinión, esta precisión conceptual puede lograrse a partir de sus características esenciales: la *interferencia* y la *competencia*. Se interfieren entre sí, desde las informaciones que inundan las capacidades de procesamiento de nuestro sistema, aún en el plano más básico o perceptual siguiendo una perspectiva 'de abajo hacia arriba', hasta las tareas a ejecutar o decisiones a tomar evidenciando una perspectiva 'de arriba hacia abajo'. Compiten a su vez por estructuras, recursos y procesos, desde los metafóricos filtros, recursos o analizadores, hasta aquellos con un sentido fisiológico más real como las vías neurales, los campos receptivos o los flujos energéticos.

De la interrelación entre interferencia y competencia se derivan los demás aspectos interesantes al abordar el tema de la atención. De tal relación se desprenden las necesidades estratégicas y ecológicas de seleccionar (priorizar temporal, cuantitativa y/o cualitativamente) unas informaciones sobre otras, y focalizar o dividir la atención sobre dichas informaciones, más alla del grado mayor o menor de conciencia que intervenga en tales procesos.

Atención selectiva

Desde las primeras definiciones de la atención se planteó que "la focalización, concentración, de la conciencia son su esencia. Implica despreciar algunas cosas para tratar efectivamente con las otras" (James, 1890).

Existe un fenómeno conocido como "fiesta de coctel" (descrita por Cherry, 1953) en el cual una persona en medio de una fiesta puede concentrarse en la conversación de su interés, ignorando el resto de las conversaciones sostenidas al mismo tiempo por otras personas. A partir de este fenómeno, el propio Cherry desarrolló un conjunto de trabajos experimentales, utilizando la técnica de seguimiento de un mensaje en un diseño de presentación dicótica, en los cuales demostró la posibilidad de identificar algunas características muy básicas del mensaje ignorado pero no sus detalles.

Si el sistema es desbordado por el ambiente con una enorme cantidad de información, éste necesariamente debe seleccionar aquella o aquellas entradas sensoriales que tratará prioritariamente. La atención selectiva es el concepto que hace referencia a tal función de la atención perceptual: seleccionar entre la cantidad de estímulos presentes, candidatos potenciales del procesamiento perceptual.

Dos preguntas guían el desarrollo de esta vertiente: Qué factores hacen más fácil y eficiente la selección? Qué consecuencias tiene la selección sobre el procesamiento ulterior de los estímulos, atendidos y no atendidos? El tipo de diseño experimental carácterístico para su estudio es la tarea de filtraje, en la cual se les presentan a los sujetos varios estímulos simultáneamente, para que reporten algún atributo del subconjunto de los estímulos que satisfaga cierto criterio de selección. El nivel de procesamiento alcanzado por los estímulos no seleccionados normalmente se explora a través de mediciones indirectas.

En el caso particular del sistema visual es necesario destacar que la selección atencional no es equivalente al mecanismo externo de los movimientos oculares. Es posible distinguir una selección atencional abierta (directa), guiada por los movimientos oculares en la exploración del campo visual y caracterizada porque el enfoque de los estímulos seleccionados siempre es foveal, y una selección atencional encubierta (indirecta), en la cual la localización escogida no coincide con el enfoque foveal pues los movimientos oculares no se dirigen hacia ella. Esta independencia relativa de la atención selectiva y los movimientos oculares no niega la relación funcional que existe entre ellos.

A partir de los estudios de la atención selectiva se han desarrollado una serie de modelos que enfatizan en la existencia de un filtro o mecanismo selector asociado al canal central de capacidad limitada. El filtro es la estructura que determina el cuello de botella en el flujo de la información y que representa el punto de tránsito de un procesamiento perceptual en paralelo al procesamiento en serie de las entradas informacionales.

Generalmente los diferentes modelos de filtro son analizados a partir de su ubicación en un continuum en función de la etapa de procesamiento en la que está dispuesto el filtro. Un análisis más profundo (Pashler, 1998) sugiere que no difieren en una dimensión, sino en la forma en que responden a dos preguntas fundamentales: El procesamiento de varios estímulos presentados al mismo tiempo es serial o paralelo? Qué nivel de procesamiento alcanzan los estímulos rechazados (no atendidos)? Llegan a identificarse? Veamos algunos de estos modelos:

Selección temprana (filtro rígido precategorial)

Cuando se plantea que la selección ocurre temprano en la corriente de procesamiento, el término "temprano" no se refiere directamente al tiempo, sino a la secuencia de etapas del procesamiento. El modelo más representativo de este tipo de selección, basado en evidencias experimentales (Broadbent, 1958), es el modelo de filtro rígido.

Broadbent propone que todos los estímulos que llegan al sistema sensorial son procesados hasta un punto en el cual ciertos atributos físicos (localización, intensidad, etc.) son analizados en paralelo y representados explícitamente; la identificación de los estímulos, sin embargo, sólo es posible serialmente. Es necesaria entonces la existencia de una estructura o dispositivo (filtro selector) responsable del filtraje para determinar qué estímulos recibirán un procesamiento más profundo. El filtro funciona sobre la base del análisis preliminar de (sintonizándose con) los atributos físicos elementales.

Selección tardía (filtro poscategorial)

Algunos datos (Deutsch y Deutsch, 1963; Norman, 1968) muestran que el reconocimiento de estímulos u objetos familiares se desarrolla sin límites de capacidad, al no haber interferencia entre la identificación simultánea de varios estímulos, y sin carácter selectivo. Esto no quiere decir que todos los estímulos presentes son necesariamente identificados, sino que no es posible seleccionar voluntariamente si identificar o no un estímulo determinado.

Se asume que el procesamiento selectivo, de carácter serial y sujeto a límites de capacidad, comienza una vez que el análisis categorial (identificación) se ha completado. Como los sujetos parecen no ser conscientes de la mayoría de los estímulos ignorados, se plantea que la conciencia depende de los mecanismod subsiguientes en el procesamiento selectivo.

Proponen que independientemente de lo que se decida atender o ignorar, el mecanismo neural que reconoce un estímulo como perteneciente a una categoría familiar realiza su operación para todos aquellos estímulos que arriven con la calidad sensorial adecuada para ello (no así en el caso de categorizaciones complejas). Cuando varios estímulos son presentados simultáneamente, son procesados hasta ser identificados en paralelo, y sólo en lo adelante (en los niveles ejecutivos) el procesamiento se hará serial y seleccionará uno de los estímulos ya identificados.

Modelo de filtro atenuador

Más allá de la etapa de procesamiento en la que opera el filtro, Treisman (1960) postula que éste no tiene por qué ser pensado como un mecanismo rígido y dicotómico de "todo o nada". Los mensajes rechazados, en lugar de ser totalmente bloqueados, son atenuados (parcialmente filtrados). Los estímulos no atendidos (atenuados) no producen una activación suficiente para alcanzar el umbral de su detección; sin embargo, cuando representan un concepto que ha sido recientemente activado, sí se alcanza el umbral. El reconocimiento se produce a partir de la acumulación de información y de la activación de las unidades de detección.

Procesamiento en paralelo controlado (filtro estratégico)

Es posible la existencia de un mecanismo de selección estratégico (Pashler, 1998). Cuando es conveniente o necesario, según las demandas de la tarea (por ej.: una situación de elevada carga perceptual), atender un estímulo e ignorar el resto, es lógico (y funcional) pensar que el estímulo rechazado no se analice más allá del nivel de sus atributos físicos (como en la selección temprana). Cuando es conveniente o necesario atender a más de un estímulo a la vez (por ej.: cuando deben compararse dos objetos), ambos pueden ser identificados en paralelo (como en la selección tardía). El sistema lleva cabo el procesamiento más ventajoso según las exigencias de la tarea.

Resultados más relevantes de los estudios de atención selectiva

Siguiendo a Pashler (1998) es posible enunciar ciertas generalizaciones a partir de la contrastación de los estudios más relevantes realizados siguiendo esta línea: Cuando la atención se focaliza sobre (selecciona) unos estímulos y rechaza otros, generalmente sólo es posible reportar las propiedades físicas elementales de los estímulos no atendidos. Bajo determinadas condiciones, aún manteniéndose la selectividad atencional, se reporta a través de mediciones indirectas el análisis categorial (incluso semántico) de algunos de los estímulos no atendidos.

Atención dividida

Algunas críticas a los modelos de filtro formularon que los procesos de selección de la información no requieren ningún mecanismo o estructura específica (Neisser, 1976), considerando al filtro como un constructo simple e innecesario y una metáfora inadecuada. Se abandonó entonces el enfoque estructural, desarrollándose una perspectiva más dinámica y centrada más en los límites de la atención que en su función selectiva.

William James (1890) dijo: "Si la pregunta original de cuántas ideas o cosas pueden ser atendidas de una vez significa cuántos sistemas o procesos enteramente desconectados pueden ponerse en marcha simultáneamente, entonces la respuesta es: no más de uno fácilmente, a no ser que sean muy habituales".

Son igual de cotidianas una situación en la cual una persona es capaz de llevar a cabo varias operaciones al mismo tiempo y aquella otra en la cual ésto parece prácticamente imposible. Si la capacidad atencional es limitada, deberá distribuirse entre el número de estímulos a procesar. Si la cantidad y/o dificultad de los procesamientos simultáneos exceden dicha capacidad, se producirán costos en la ejecución de alguno o de todos ellos. El concepto de atención dividida enfatiza en estos aspectos.

Dos preguntas guían el desarrollo de esta vertiente: Es realmente limitada la capacidad de los sistemas perceptuales para procesar varias entradas de información en paralelo? Cuál es la naturaleza de esta limitación? Este enfoque tiene cierta inspiración económica, pues postula que la atención es un sistema de recursos limitados que se distribuyen entre las tareas concurrentes. El tipo de diseño experimental carácterístico para su estudio es el de dobles tareas (Posner, 1978; Logan, 1978, 1979), en el cual se pide a los sujetos que realicen dos tareas relativamente simultáneas, considerándose la demanda atencional de una de ellas a partir del grado de deterioro de la ejecución de la otra.

También se ha utilizado la búsqueda visual (Estes y Taylor, 1964), en la cual los sujetos deben reportar la presencia o no de un estímulo "diana" tras examinar una imagen visual que contiene varios elementos, considerándose la eficiencia de la detección en función del número de elementos contenidos en la imagen. Este diseño tiene el inconveniente de que la pérdida de eficiencia como consecuencia del incremento del número de elementos presentados puede no estar estrictamente provocada por los límites de capacidad, pues puede explicarse por un efecto estadístico de acumulación del ruido de los procesos decisorios.

Otro diseño experimental ampliamente utilizado es la presentación de elementos simultáneamente en una imagen visual o en imágenes sucesivas (Eriksen y Spencer, 1969; Shiffrin y Gardner, 1972; Kleiss y Lane, 1986), en el cual se mantiene constante el número de elementos presentados (para evitar el efecto estadístico anteriormente mencionado) y se varía el instante de tiempo relativo en que se presenta cada elemento (todos juntos, o uno a continuación del otro). Se considera que si hay límites de capacidad, los juicios serán menos precisos cuando todos los elementos deban ser procesados al mismo tiempo; de lo contrario, se asume un análisis perceptual en paralelo.

Al asumir la atención como un sistema de recursos limitados se entiende por recursos un tipo de energía o de estructuras (unidades) de procesamiento, más o menos especificas. Se han desarrollado diversos modelos de atención dividida fundamentalmente en función de cómo se conciben la especificidad de los recursos.

Modelo de administración de recursos centrales

El primer modelo de capacidad atencional limitada (Kahneman, 1973), marcado por una metáfora economicista, postula que la atención funciona como un administrador central de recursos. Este administrador evalúa las demandas que realizan al sistema las diferentes operaciones a desarrollar, realizando luego la asignación de recursos siguiendo una política de distribución en función de la capacidad disponible.

La política de distribución para la asignación de los recursos atencionales depende de varios factores. Entre estos factores se encuentran la propia evaluación de demandas (consumo relativo de cada tarea), las disposiciones duraderas (reglas que rigen la atención involuntaria), las intenciones momentáneas (criterios selectivos activados en un momento dado), y el nivel de activación general del sujeto. Los recursos atencionales que se asignan se extraen de un "pozo"general que determina la capacidad disponible.

Kahneman finalmente plantea que la interferencia entre dos tareas puede ser de capacidad, si ambas compiten únicamente por los recursos centrales inespecíficos, o estructural, si ambas compiten por alguna estructura perceptiva. Norman y Bobrow (1975) amplían el modelo de Kahneman. Proponen que la ejecución de una tarea puede estar limitada no sólo por los recursos, sino además por los datos, tanto los que llegan y los almacenados (calidad de la señal y de la representación mental con ella relacionada).

Modelo de recursos específicos

Navon y Gopher (1979) critican la dualidad del modelo de Kahneman que aún sostiene la posibilidad de una fuente de interferencia estructural en un modelo de recursos. Como solución a las interferencias específicas proponen la multiplicidad de recursos: cada tarea particular demanda recursos específicos, mientras otros le son irrelevantes; la interferencia entre dos tareas se produce cuando demandan el mismo tipo de recursos.

Resultados más relevantes de los estudios de atención dividida

Siguiendo a Pashler (1998) es posible enunciar ciertas generalizaciones: Al elevar la complejidad (demanda atencional) de las tareas, incrementando la carga perceptual, disminuyendo la discriminabilidad estímulo "diana"-distractor, o aumentando la cantidad de estímulos "diana" a procesar, se hacen evidentes las limitaciones de recursos atencionales. La dificultad para procesar simultáneamente varios estímulos "diana" parece responder a un mecanismo diferente al que opera en la discriminación estímulo "diana"-distractor.

La naturaleza de la limitación puede estar dada por limitaciones en la transmisión de la información (Nakayama, 1990; Verghese y Pelli, 1992), o por la interferencia entre las diferentes representaciones activadas en una misma red neural (Mozer, 1991). No obstante, es necesario aclarar que hablar en términos de capacidad o recursos resulta un poco vago y no tiene un fundamento explícito en la fisiología del sistema nervioso. Por otra parte, los límites en la capacidad atencional no son fijos, dependen de la práctica y de las habilidades individuales individuales; quizás sería mejor hablar de habilidades en lugar de recursos, y entonces la búsqueda de su límite último sería un contrasentido.

Atención basada en los analizadores o discriminadores

Como una derivación híbrida de los modelos estructurales y dinámicos, y apuntando en la misma dirección de los modelos de recursos múltiples (intentando explicar también la especificidad de las interferencias), Allport (1971) propone que el análisis perceptual tiene lugar en diversos sistemas de analizadores, cada uno relacionado con un atributo particular del estímulo.

Si las discriminaciones involucran diferentes analizadores, éstas no se interfieren; si compiten por el mismo analizador, la interferencia aparece. Esta teoría predice bajos niveles de ejecución en pares de tareas que demanden la realización de un mismo tipo de juicio, comparados con los alcanzados en pares de tareas que demanden la realización de juicios diferentes. El diseño esperimental utilizado para demostrar este enfoque se basa en la combinación de ambos tipos de condiciones.

El resultado más importante de este enfoque es que se ha demostrado que tareas que implican el procesamiento de un mismo atributo perceptual se interfieren más que aquellas que discriminan entre atributos diferentes de la misma modalidad sensorial. Algo similar ocurre al comparar el procesamiento intra e intermodal. Sin embargo, estos resultados también son explicables desde otros enfoques atencionales abordados antes.

Atención visual: enfoques experimentales actuales

La información proveniente de cada una de las modalidades sensoriales, y más aún su interrelación funcional, es imprescindible para la mejor adaptación del organismo en su ambiente. La mayor parte de la estimulación es recibida por la vía visual, que nos permite procesar, con un alto grado de resolución y fidelidad, la gran multiplicidad de mensajes en forma de imágenes que se nos presenta. Es por eso que la investigación en torno a la atención visual, guía del procesamiento de la información visual, ha adquirido protagonismo en los últimos años.

En la actualidad, el amplio debate teórico de la atención visual no se concentra alrededor de los temas clásicos antes expuestos. De cierta forma se ha superado la discusión a partir de modelos muy generales (filtros, recursos, analizadores) que intentan explicar la naturaleza (selectiva, dividida) del proceso atencional, encaminándose hacia la caracterización de aspectos más específicos y abordables. Existen entonces algunas preguntas claves que orientan el desarrollo experimental y teórico.

La primera de ellas se refiere a las bases sobre las cuales se establece la selección atencional. Teniendo en cuenta que los estímulos visuales son procesados en forma de múltiples representaciones internas, surge la interrogante de si existe algún tipo o tipos específicos de representación que guíen la selección: ¿qué se selecciona?

Una segunda pregunta intenta lograr una caracterización temporal del proceso de la selección atencional. Se trata de establecer la duración de la fijación atencional en la representación seleccionada, así como los límites temporales existentes para los desplazamientos de la atención de una representación a otra: ¿cuál es la dinámica temporal de la selección?

La tercera pregunta aborda el problema de las bases fisiológicas que explican la selección en base a uno u otro tipo de representación. Lo anterior puede arrojar luz sobre la etapa o nivel de procesamiento de la información visual en la cual ocurre la selección. Se intenta evitar la aparición de propuestas demasiado metafóricas y ajenas a los conocimientos que ya se poseen acerca del funcionamiento del sistema visual: ¿cuál es la implementación neural?

Así tenemos que, en dependencia de cómo responden a las preguntas anteriores, se delinean los diversos modelos teóricos. La respuesta a la primera pregunta, qué tipo de representación establece las bases de la selección atencional, es la clave que determina en buena medida las demás respuestas, que más bien contribuyen a instrumentar cada modelo particular.

En los últimos años la polémica ha girado en torno a dos modelos que, si bien no son necesariamente excluyentes, se han situado en posiciones extremas. Estos modelos postulan que la selección puede ser espacial (la atención se dirige hacia una localización específica de la escena visual), u orientada a los objetos (se selecciona un objeto perceptual derivado de la organización previa de la escena). La naturaleza misma del tipo de representación que postulan como básico para la selección (localizaciones espaciales u objetos perceptuales) determina las restantes características de los modelos.

¿Qué se selecciona?

Atención basada en el espacio

En la mayoría de los estudios realizados siguiendo el enfoque de la atención selectiva (resumidos en Pashler, 1998), se observa que la selección es típicamente más fácil cuando se utiliza como criterio selectivo la localización espacial que cuando se basa en otros criterios tales como el color, el tamaño, etc. Por otra parte, cuando los sujetos detectan la presencia de un estímulo "diana" definido a través de otros atributos y no de su localización espacial, son capaces además de reportar dicha localización. Al mismo tiempo, cuando la localización es incorrectamente reportada, la detección del estímulo "diana" empeora (Shiffrin y Gardner, 1972; Johnston y Pashler, 1991; Graham, 1989; Nissen, 1985). La relevancia de la localización espacial como un atributo especial se pone de manifiesto incluso en tareas en las cuales no sólo no es el criterio de selección, sino ni siquiera el atributo a reportar. Snyder (1972) demostró que los errores cometidos en una tarea de identificación de letras se concentraban en las localizaciones vecinas a la del estímulo "diana".

Todos estos datos experimentales, y la ya descrita organización topográfica del sistema visual, que descubre en las representaciones de los demás atributos un carácter ordenado en forma de mapas que conservan aproximadamente las relaciones espaciales existentes en la escena visual, reafirman la importancia del espacio. Esta reafirmación refuerza la noción intuitiva de que dos objetos no ocupan el mismo lugar en el espacio, o un mismo objeto dos lugares diferentes. La localización espacial juega un rol diferente al de otros atributos en la selección visual. Quizás no sea necesariamente un criterio de selección más efectivo, pero sí pudiera pensarse que es, de cierto modo, más primario. La selección a través de otros atributos puede ser interpretada como una selección mediada por otra anterior, basada en el espacio.

El postulado fundamental de las diferentes variantes clásicas del modelo de la atención espacial, como esbozamos anteriormente, propone que los estímulos se representan en base a su localización dentro de un sistema de coordenadas espaciales geométricas centradas en el sujeto. Por lo tanto, la selección atencional se basa en la selección primaria de localizaciones espaciales específicas dentro de las representaciones del campo visual. Sólo es posible focalizar la atención sobre un lugar determinado en cada instante de tiempo. Toda la información que está comprendida dentro de este foco es atendida y, por tanto, procesada prioritariamente, en tanto se ignora toda la información que queda fuera.

Una de las técnicas experimentales que más desarrollo ha promovido dentro de este modelo es el pre-aviso espacial (Posner, 1978). En estos estudios los sujetos debían, con la vista fija en el centro de la pantalla, detectar lo más rápidamente posible la aparición de un estímulo. El estímulo aparecía a la derecha o a la izquierda del punto de fijación. Su ubicación se avisaba previamente a través de una señal (pre-aviso válido). En un por ciento pequeño de los eventos la señal indicaba una posición errónea (condición de pre-aviso no válido); en otros eventos no se proporcionaba el pre-aviso o éste no aportaba información sobre la posición en la cual aparecería el estímulo (condición neutral). Los tiempos de reacción en la condición de pre-aviso válido fueron menores que en la condición neutral, y éstos, a su vez, menores que los de la condición de pre-aviso no válido.

Tanto la ventaja observada al detectar estímulos que ocurren sobre una localización espacial previamente avisada, como la desventaja que se manifiesta cuando los estímulos se presentan en una localización espacial diferente de la previamente avisada, llevaron a algunos autores (Posner, 1980; Posner, 1978; Hoffman, Nelson y Houck, 1983) a formular la metáfora del reflector. La atención es considerada como un foco que se dirige hacia una región espacial particular; lo que 'ilumina' es lo atendido, lo que queda 'en la sombra', lo rechazado. Dicho reflector atencional tiende a ubicarse en la fóvea, pero puede dirigirse a la visión periférica.

Según esta analogía, la necesidad del cambio de la atención (del reflector) de un sitio a otro explica la desventaja observada en la condición de pre-aviso no válido. Cuatro etapas diferentes se verían implicadas: enganche de la atención en la localización pre-avisada (común para cualquier condición), y adicionalmente, desenganche de la localización pre-avisada, desplazamiento del reflector, y re-enganche en la verdadera (nueva) localización. La ventaja observada en la condición de pre-aviso válido con respecto a la condición neutral puede explicarse porque la primera etapa puede realizarse antes de la presentación del estímulo, de modo que el reflector puede dirigirse anticipadamente, y concentrarse, en la región donde luego aparece el estímulo.

Basándose en la analogía del reflector, y utilizando como técnica experimental la búsqueda visual, Treisman (1988) desarrolló otra teoría perteneciente a los modelos espaciales. Como en toda tarea de búsqueda visual, los sujetos debían reportar la presencia o no de un estímulo "diana", tras examinar una imagen visual que contenía un número variable de elementos distractores. La eficiencia de la detección es analizada en función del número de elementos contenidos en la imagen.

Treisman comparó dos condiciones experimentales. En la condición de búsqueda de rasgos, el estímulo "diana" se diferenciaba fácilmente de los distractores teniendo en cuenta un sólo atributo (por ej.: buscar una T roja entre Ts verdes). En la condición de búsqueda de conjunciones de rasgos, el estímulo "diana" compartía atributos específicos con determinados subconjuntos de distractores, en tanto sólo se diferenciaba del conjunto total de los distractores a partir de una conjunción de atributos (por ej.: buscar una T roja entre Ts verdes y Ls rojas).

La eficiencia de la detección del estímulo "diana" (medida en tiempos de reacción), en función del incremento del número de distractores presentes en la escena visual, presentó dos patrones bien diferentes en las dos condiciones experimentales. En la búsqueda de rasgos no se incrementaron los tiempos de reacción con el aumento del número de distractores, evidenciándose un procesamiento en paralelo de los estímulos. En la búsqueda de conjunciones de rasgos los tiempos de reacción aumentaron linealmente con el incremento del número de distractores, evidenciándose un procesamiento serial de los estímulos (Treisman y Gelade, 1980; Treisman, 1988; Treisman y Sato, 1990; Wolfe, Cave y Franzel, 1989).

A partir de estos resultados, Treisman (1988) formula su Teoría de la Integración de Rasgos, en la cual formula que la información visual es procesada en dos estadios sucesivos. Primero, se define espacialmente cada uno de los atributos o rasgos elementales del estímulo en un registro independiente (en los llamados mapas de rasgos) y en paralelo, a través de todo el campo visual. Luego la conjunción de los rasgos (percepción de un objeto) sólo es posible a partir de la focalización de la atención en una localización espacial particular (Treisman, 1988; Nakayama y Silverman, 1986).

El reflector atencional actúa como una especie de pegamento que vincula los rasgos aislados presentes en una región espacial específica, y debe recorrer el campo visual de forma serial para garantizar una adecuada y precisa integración de los rasgos; si se impide que el foco atencional se concentre, los rasgos se combinarían incorrectamente dando lugar al fenómeno visual de las conjunciones ilusorias (Prinzmetal, 1981).

Principios básicos de la atención espacial

Según los modelos espaciales clásicos, la distribución de la atención sobre el espacio visual está sujeta a reglas geométricas que determinan que el foco atencional (y la región espacial seleccionada) sea indivisible, continuo y convexo (Yantis, 1992; Nakayama y He, 1995; Heinze, Luck, Münte, Gos, Mangun y Hillyard, 1994). El mejor ejemplo de este principio es el antes comentado modelo del reflector (Posner, 1980), donde toda la información comprendida dentro del foco es atendida y procesada prioritariamente, en tanto se ignora toda la información que queda fuera.

Existen otros modelos que, aunque incorporan modificaciones en las propiedades del foco, cumplen el principio de su forma, continuidad e indivisibilidad. Eriksen y St. James (1986) postulan que el reflector funciona como un sistema de lentes que ajustan su apertura en dependencia del área de la localización espacial que se requiere enfocar; mientras más área abarque el foco (menos concentrada sea la atención), menos precisas serán las discriminaciones sobre los eventos que en su interior ocurran.

También es posible plantear, sin violar el principio referido a las características del foco, que la atención no se distribuye en su interior de una manera homogénea, sino en forma de gradiente (Downing, 1988). La atención se concentra hacia la región central del foco y se va haciendo cada vez más difusa en la medida en que nos alejamos hacia la periferia.

El hecho de considerar el foco atencional como convexo, unitario y continuo implica diferentes consecuencias (revisadas en Lavie y Driver, 1996). Entre ellas se destacan los otros dos principios básicos: la proximidad espacial y la inercia espacial, imprescindibles para afirmar la existencia de un mecanismo atencional basado en el espacio.

La inercia espacial consiste en que una vez que la atención ha sido dirigida a una localización espacial determinada, debe transcurrir cierto tiempo antes de que pueda ser dirigida a una nueva localización. Como resultado, la presencia de un estímulo "diana" en una localización facilita la discriminación de un estímulo "diana" posterior en la misma localización (pre-activación espacial), en tanto la entorpece si ocurre en un lugar diferente (incluso si de antemano se conoce que el segundo estímulo "diana" nunca ocurrirá donde el primero).

La proximidad espacial consiste en que es más fácil (eficiente) discriminar entre dos estímulos mientras más cercanos se encuentren (Hoffman y Nelson, 1981; Hoffman, Nelson y Houck, 1983; Downing y Pinker, 1985; Eriksen y Eriksen, 1974; Sagi y Julesz, 1986). En la medida en que dos estímulos estén más próximos entre sí, 1) tienen más probabilidad de ser abarcados por el mismo 'reflector', 2) es posible enfocar el 'sistema de lentes' y concentrar la atención sobre un área menor, y/o 3) tienen más probabilidad de estar en la zona central del 'gradiente' donde es mayor la concentración atencional.

La acción de ambos principios puede observarse en una serie de experimentos de LaBerge y cols. (LaBerge y Brown, 1989; LaBerge, Carlson, Williams y Bunney, 1997). Se pre-avisaba una localización espacial y se presentaba brevemente un arreglo de símbolos compuesto por un estímulo "diana", presentado en la posición pre-avisada, rodeado de distractores. Luego se presentaba un segundo arreglo de símbolos variando la posición del estímulo "diana", de modo que la distancia entre las posiciones relativas de ambos estímulos "diana" también variaba.

Los sujetos debían responder lo más rápido posible a ciertos pares de estímulos "diana". Las respuestas más rápidas se obtuvieron cuando el segundo estímulo "diana" reemplazaba al primero en la misma posición (beneficio de la inercia espacial). A medida que crecía la distancia entre las posiciones de ambos, las respuestas se hicieron cada vez más lentas (beneficio de la proximidad espacial).

Atención orientada a los objetos

La otra perspectiva acerca del tipo de representación que se selecciona tiene sus orígenes en James (1890), quien planteó que "independientemente de cuán numerosas fueran las cosas a las cuales uno atiende, sólo pueden ser conocidas en un único pulso de conciencia, en el cual forman un 'objeto' complejo". Neisser (1976) fue, muchos años después, el promotor contemporáneo de la idea de que nuestros límites atencionales en el mundo visual están definidos por la cantidad de objetos que podemos atender al mismo tiempo.

Neisser propuso que el análisis perceptual del campo visual se desarrolla en dos etapas sucesivas: primero la imagen se segmenta en objetos independientes y luego se selecciona uno de esos objetos. La focalización de la atención es secuencial (sobre un solo objeto en cada momento), y en ella el espacio juega un papel secundario. En un ingenioso experimento Neisser y Becklen (1975) demostraron que es posible atender selectivamente a una de dos imágenes complejas superpuestas. Aunque ambas escenas visuales coincidían sobre una misma región del campo visual, los sujetos eran capaces de detectar los cambios ocurridos en el contenido de la imagen atendida, pero no aquellos (por muy relevantes que fueran) que tenían lugar en la superficie ignorada (replicado luego por Rock y Gutman, 1981).

En los modelos espaciales clásicos, anteriormente revisados, el espacio desempeña el rol decisivo en la selección y distribución atencional, no otorgándosele ninguna importancia a la organización perceptual de la escena visual. Los modelos que proponen una atención orientada a los objetos parten de considerar que es poco económico atender a las localizaciones espaciales con independencia de si éstas están o no ocupadas por objetos. Postulan que la selección y distribución atencional se dirige a representaciones más complejas (integran varios atributos elementales), las cuales son el resultado de los procesos perceptuales pre-atentivos básicos que organizan previamente la escena visual.

Esas representaciones complejas son, además, múltiples; lo cual se ha evidenciado no sólo experimentalmente, sino en la clínica neuropsicológica. Se conocen diversos trastornos (por ej.: anomias, agnosias, apraxias, etc.) que afectan selectivamente uno o varios tipos de estas representaciones. Por otra parte, debido a las diferencias de localización de las lesiones que originan unas u otras alteraciones, se ha pensado en que podrían activarse en estructuras neurales diferentes.

La multiplicidad de representaciones no implica de ningún modo que los diversos tipos de representaciones parciales sobre un objeto determinado sean absolutamente independientes y mucho menos excluyentes, sino todo lo contrario: es muy probable que se activen simultáneamente complementando funcionalmente la información sobre dicho objeto.

Treisman y Kanwisher (1998), por ejemplo, proponen la existencia de distintos tipos de representaciones de orden superior. Existen representaciones estructurales, que establecen la relación del objeto como un todo con las partes que lo componen, así como la relación de las partes entre sí. También es posible hablar de representaciones de identidad, que participan de la clasificación categorial y/o semántica de un objeto como perteneciente a un tipo determinado. Algunas se basan en el conocimiento previo, vinculando al objeto y sus características con la experiencia anterior. Otras son representaciones emocionales y motivacionales, relacionando un determinado objeto con su contenido afectivo. Además, existen representaciones centradas en las acciones conductuales, a partir de los posibles usos prácticos de los objetos. Por último tenemos representaciones espacio-temporales, en las cuales se codifican y actualizan las transformaciones que ocurren en los objetos, permitiendo la continuidad, estabilidad y permanencia perceptuales.

El desarrollo de los modelos de la atención orientada a los objetos no ha particularizado tanto en la diversidad de las posibles representaciones. De forma general han operado con un concepto amplio de 'objeto' en tanto entidad perceptual compleja e independiente, definida por una conjunción de atributos perceptuales con significado psicológico propio. Así, han planteado que la atención selecciona entre objetos (Duncan, 1984), grupos perceptuales (Duncan y Humphreys, 1989), o superficies (Nakayama y He, 1995; He y Nakayama, 1995), siendo todos ellos representaciones derivadas de los procesos perceptuales pre-atentivos básicos que organizan previamente la escena visual.

Kahneman, Treisman y Gibbs (1992) han puesto énfasis en el carácter dinámico y flexible de las representaciones, proponiendo la existencia de los 'archivos de objeto'. Estos 'archivos de objeto' son representaciones de orden superior que integran varios rasgos o atributos elementales –entre ellos el espacio-, y que tienen un carácter temporal, episódico y modificable, pues se actualizan a partir de las nuevas informaciones sensoriales que las transforman.

Un ejemplo tomado de la naturaleza sería el de un camaleón que cambia de color, de posición, proyecta el pañuelo, o incluso se desplaza, pero se percibe como el mismo camaleón. Pudiera parecer, a partir de este ejemplo, que los 'archivos de objeto' hacen referencia a una representación flexible pero invariante en cuanto a la identidad del ente percibido. En realidad, los 'archivos de objeto' también asimilan (actualizan) modificaciones de identidad, lo cual se evidencia en el propio ejemplo citado por los autores del término, tomando como referencia la presentación de las historietas de Superman: “es un avión..., es un pájaro..., es Superman!”.

Este tipo de representación permite, tanto la unidad e integración de información sensorial cambiante en un mismo objeto perceptual (continuidad espacio-temporal), como la percepción simultánea e individualizada de varios objetos idénticos (instanciación). La atención produce, según este enfoque, supresiones o activaciones, perdurables en el tiempo, de las representaciones neurales de dichos ‘archivos de objeto’ y de los eventos que los afectan.

Los intentos de demostrar experimentalmente la existencia de una selección orientada a los objetos implica un difícil reto. Como se ha visto, uno de los atributos que caracterizan un objeto es su localización espacial (un objeto es de un color particular, una forma, un tamaño, una textura, etc., pero también está ubicado en un lugar específico del campo visual). Por otra parte, dos objetos diferentes no ocupan una misma localización en el espacio, del mismo modo que un único objeto no suele ocupar dos localizaciones espaciales separadas (no continuas). El espacio que un objeto ocupa no es, entonces, un simple atributo más, sino que generalmente puede funcionar como una pista inequívoca para guiar la atención.

Esta situación ha contribuido a la dominancia durante años de los modelos espaciales (Treisman, 1988; Theeuwes, 1993). Los modelos que postulan la atención orientada a los objetos se han visto obligados a demostrar, no sólo la existencia de la interferencia y competencia entre los objetos, sino que tales interferencia y competencia no pueden ser explicadas por la acción de mecanismos espaciales. Esta necesidad de disociar los efectos atencionales debidos a la competencia entre objetos derivados de la organización perceptual de aquellos puramente espaciales, complica metodológicamente los diseños experimentales.

Estos diseños experimentales que intentan restringir la acción de los mecanismos espaciales, o contraponerlos a la organización perceptual, han seguido tres direcciones fundamentales (revisadas por Egeth y Yantis, 1997). Estas tres aproximaciones se encaminan a atacar directamente a los principios básicos de la atención espacial, abordados con anterioridad.

A partir de los estudios, ya referidos, que exploraban la selección entre imágenes superpuestas (Neisser y Becklen, 1975; Rock y Gutman, 1981), se desarrolló una línea de trabajo que, utilizando la superposición gráfica de dos objetos diferentes en una misma localización espacial, atacó el principio del foco atencional indivisible, continuo y convexo.

Duncan (1984) realizó un experimento en el cual se superponían en la misma región del espacio dos objetos distintos: una línea y un rectángulo. Cada objeto tenía atributos propios que constituían los rasgos a discriminar en la tarea: la línea, discontinua o de puntos, estaba ligeramente inclinada en una u otra diagonal; en tanto el rectángulo, alto o bajo, tenía una pequeña apertura en el lado derecho o izquierdo.

Los sujetos debían realizar dos discriminaciones en cada presentación, combinándose éstas para dar lugar a dos condiciones experimentales diferentes: debían discriminarse dos atributos del mismo objeto (inclinación y textura de la línea, o altura y posición de la apertura del rectángulo), o dos atributos pertenecientes a objetos diferentes (por ej.: inclinación de la línea y altura del rectángulo).

Cuando los juicios implicaban discriminaciones sobre un mismo objeto no se produjeron costos en la ejecución de la tarea, alcanzándose una eficiencia similar a la lograda cuando debía discriminarse un sólo atributo (situación sin competencia). Cuando los juicios implicaban discriminaciones sobre distintos objetos, ambas discriminaciones se interferían provocando costos en la ejecución de la tarea.

Como ambos objetos comparten la misma región del espacio, estos resultados no son explicables teniendo en cuenta el principio del foco atencional indivisible, continuo y convexo. Es posible entonces, según Duncan (1984), hablar de selección entre objetos, al menos si se impide una selección espacial. Utilizando este tipo de diseño se han replicado los resultados descritos (Vecera y Farah, 1994; Kramer, Weber y Watson, 1997). Más aún, Vecera y Farah (1994) obtuvieron que separando espacialmente los objetos no se afectaba el costo producido por dividir la atención entre dos objetos, demostrando así que la selección basada en los objetos puede ser espacialmente invariante.

Una segunda línea de trabajo en el intento por demostrar la atención orientada a los objetos consiste en demostrar la influencia del agrupamiento perceptual, contraponiéndolo al principio de la proximidad espacial. ¿Dos juicios sobre dos estímulos se benefician más porque ambos están más cercanos, o porque forman parte de un mismo grupo perceptual? ¿La interferencia entre un "estímulo diana" y los distractores que lo rodean crece más en función de la proximidad, o de la pertenencia a un mismo grupo perceptual?

Muchos estudios, utilizando diversas tareas, han otorgado mayor peso al agrupamiento perceptual que a la distancia. Se han obtenido evidencias en esta dirección en tareas de discriminación de un estímulo "diana", presentado en el centro de la imagen y rodeado de distractores, utilizando el agrupamiento a partir del movimiento (Driver y Baylis, 1989) o del color (Bundesen y Pedersen, 1983; Baylis y Driver, 1992; Kramer y Jacobson, 1991 –aunque Tsal y Lavie, 1988, aportan un resultado contrario-). También se ha demostrado en tareas de búsqueda visual, la cual se realiza prácticamente en paralelo si los distractores pueden, mediante el movimiento común, ser agrupados (e ignorados) como un conjunto (McLeod, Driver y Crisp, 1988; McLeod, Driver, Dienes y Crisp, 1991; Driver y McLeod, 1992; Duncan, 1995).

También dentro de esta línea, existen trabajos que examinan independientemente el costo producido por el cambio de la atención de un lugar a otro de un mismo objeto (costo puramente espacial) y el costo producido por el cambio de la atención de un objeto a otro (costo de objeto, adicional al costo espacial). Estos estudios (Egly, Driver, y Rafal, 1994; Lavie y Driver, 1996; Behrmann, Zemel y Mozer, 1998) evidencian la existencia del costo de objeto más allá de la existencia o no del costo espacial.

La tercera línea que intenta aislar los efectos espaciales de aquellos provocados por la atención orientada a los objetos, ataca directamente el principio de inercia espacial. Para ello se utiliza un diseño que presenta objetos en movimiento, disociados de cualquier localización espacial fija.

Existen dos fenómenos normalmente asociados a la selección espacial que son explorados siguiendo este diseño. El primero de ellos, ya mencionado antes al tratar la inercia espacial, es la pre-activación espacial. Se encontraron evidencias en favor de una pre-activación no ya espacial sino de objeto (Kahneman, Treisman, y Gibbs, 1992; Yantis, 1992).

El segundo fenómeno, asociado con tareas de búsqueda visual, es conocido como 'inhibición de retorno', y consiste en una disminución de la probabilidad de detectar un estímulo "diana" presentado en una localización espacial que ya ha sido explorada breve tiempo antes. Se demostró que este fenómeno tampoco es exclusivamente espacial, sino que puede operar basado en los objetos (Tipper, Driver y Weaver, 1991; Tipper, Weaver, Jerreat y Burak, 1994).

Por último es necesario destacar un diseño, desarrollado por Nakayama y cols., que sigue un camino relativamente independiente al de los estudios anteriores. En sus trabajos iniciales (Nakayama y Silverman, 1986) encontraron que una tarea de búsqueda visual podía ejecutarse en paralelo si los elementos podían organizarse en diferentes planos de profundidad, comprobando así que la percepción de profundidad jugaba un rol diferente (más básico) comparado con otros atributos visuales. Esto les llevo a postular una variante tridimensional del reflector, operando en el espacio y no en el plano.

Posteriormente (Nakayama y He, 1995; He y Nakayama, 1995), utilizando imágenes estereoscópicas en tareas de atención selectiva con pre-aviso espacial, encontraron que la selección se dificultaba si los elementos se ubicaban sobre una misma superficie, con independencia de que se encontraran a diferentes profundidades. Proponen entonces que la atención se divide entre las distintas superficies que conforman la imagen, aún cuando las mismas se extienden a través de diferentes profundidades.

Nakayama y cols. demuestran que el pertenecer a una misma superficie (una forma de agrupamiento perceptual) produce mayores efectos (beneficio o interferencia, según sea el caso) que la proximidad en un espacio tridimensional. Finalmente, llegan a la conclusión de que la atención no se dirige arbitrariamente a puntos o volúmenes en el espacio abstracto, sino que se orienta a las superficies, las cuales constituyen una representación intermedia entre la percepción de los rasgos elementales y el reconocimiento de los objetos (Nakayama, He y Shimojo, 1995).

Principios básicos de la atención orientada a los objetos

Los trabajos realizados por Duncan (1984) utilizando la superposición gráfica de dos objetos diferentes en una misma localización espacial, como se describió antes, obtuvieron dos resultados fundamentales: Por una parte, demostraron la existencia de interferencia entre dos discriminaciones sobre atributos de objetos diferentes; por la otra, evidenciaron que cuando se discriminan atributos de un mismo objeto no se producen costos en la ejecución de la tarea, alcanzándose una eficiencia similar a la lograda cuando debe discriminarse un sólo atributo (situación sin competencia).

Estos resultados lo llevaron a formular los principios básicos de la atención orientada a los objetos, la cual en su modelo más clásico postula que una vez que han tenido lugar los procesos de organización perceptual, la atención selecciona uno de los objetos que componen la escena visual para procesarlo con prioridad. Los principios que rigen dicha selección son: 1) Las representaciones de dos objetos diferentes se interfieren, compiten entre sí; y 2) La representación del objeto seleccionado se activa en su conjunto como una unidad, en la cual, todas sus partes y atributos se procesan con igual prioridad, sean o no relevantes para la realización de la tarea.

Estos principios se apoyan en una concepción fisiológica que ha dado lugar a un enfoque teórico (Duncan, 1990), según el cual, la selección atencional de un objeto determinado se basa en la integración funcional del procesamiento de todos sus atributos, lo cual sería posible fisiológicamente a partir de la excitación conjunta de aquellas neuronas cuyos campos receptivos procesan atributos de un mismo objeto, y de la competencia que las mismas establecen con (la inhibición de) aquellas otras neuronas cuyos campos receptivos procesan atributos de otro objeto.

¿Cuál es la dinámica temporal de la selección?

Al procesar una escena natural no sólo es necesario seleccionar una fuente de información. Es también imprescindible reposicionar la atención entre los objetos que la componen. La duración de estos cambios atencionales han sido estimadas lo mismo como muy breves que como mucho más duraderas. Estas grandes discrepancias sostienen diferentes teorías (seriales o paralelas) de la atención.

Como ya se expuso, en tareas que implican la búsqueda visual de estímulos definidos por conjunciones de rasgos (demandantes de atención), los tiempos de reacción aumentan linealmente con el incremento del número de distractores (Treisman y Gelade, 1980; Treisman, 1988; Treisman y Sato, 1990; Wolfe, Cave y Franzel, 1989). La pendiente que refleja tal incremento lineal ha dado lugar a la interpretación, basada en la suposición de que los estímulos se procesan serialmente, de que el tiempo requerido para desplazar secuencialmente el foco atencional de una localización espacial a otra es relativamente breve (pocas decenas de milisegundos).

Del mismo modo, los trabajos referidos que han abordado el principio de la proximidad espacial (Hoffman y Nelson, 1981; Hoffman, Nelson y Houck, 1983; Downing y Pinker, 1985; Eriksen y Eriksen, 1974; Sagi y Julesz, 1986), podrían también ser interpretados en términos de la dinámica temporal de los desplazamientos de la atención. Mientras más cercanos estén dos estímulos, menor será la distancia que deberá recorrer el foco atencional al desplazarse de una localización a otra y menor el tiempo necesario para el cambio atencional.

Esta interpretación supone un desplazamiento continuo a través del espacio visual entre los estímulos. Lo anterior no tiene que ser necesariamente así. Como se expresó, existen posiciones (Duncan, 1984; Vecera y Farah, 1994) que argumentan que es poco económico atender a las localizaciones espaciales con independencia de si éstas están o no ocupadas por objetos. Es posible entonces que los desplazamientos de la atención de una región del espacio a otra ocurran de forma discreta e independiente de la distancia que las separe (Yantis, 1988).

Por otra parte, los resultados de la mayoría de los estudios que demuestran la atención orientada a los objetos sugieren que una vez que la atención se dirige a la percepción de un atributo en un objeto determinado, se dificulta la percepción de un atributo en otro objeto. Una pregunta interesante es si esta limitación es absoluta o puede reflejar, al menos parcialmente, la distribución de la atención a lo largo del tiempo.

Uno de los diseños experimentales utilizados para desentrañar la naturaleza temporal de la atención orientada a objetos consistió en la presentación (y luego el enmascaramiento) de dos estímulos perceptuales en diferentes localizaciones espaciales y separados entre sí por un período de tiempo variable (Duncan, Ward y Shapiro, 1994). En este estudio se obtuvo que el procesamiento del primer estímulo interfería el procesamiento del segundo, si el intervalo temporal transcurrido entre las presentaciones del primer y el segundo estímulo era corto.

El tiempo durante el cual la atención se encuentra atrapada por el procesamiento del primer estímulo, deducido por el mayor intervalo para el cual aún se produce interferencia sobre el procesamiento del segundo, es conocido como tiempo de estacionamiento atencional (Ward, Duncan, y Shapiro, 1996; Ward, Duncan, & Shapiro, 1997). Estas investigaciones sugieren que la atención se mantiene ligada a un objeto durante algunos cientos de milisegundos antes de quedar libre para procesar otro objeto. Esta medida refleja una dinámica temporal con magnitudes de un orden superior al tiempo estimado para los desplazamientos de la atención espacial.

Los trabajos anteriormente examinados tienen un inconveniente: La atención debe transitar entre objetos presentados en localizaciones espaciales diferente. Por tanto, puede surgir la duda de cuánto del tiempo de estacionamiento atencional se debe al cambio de una localización espacial a otra.

El "parpadeo atencional" es otro fenómeno que, aunque de cierto modo tiene una naturaleza diferente, es consistente con los resultados anteriores pero excluye la explicación espacial. El diseño experimental para su estudio consiste en la presentación serial y rápida de varios estímulos (estímulos "diana" distribuidos temporalmente entre distractores) en el mismo lugar del espacio. El procesamiento del primer estímulo "diana" interfiere (impide) la detección de un segundo estímulo "diana" durante varios cientos de milisegundos (Raymond, Shapiro y Arnell, 1992; Shapiro, Raymond y Arnell, 1994).

Bases neurales

El estudio de las bases fisiológicas que participan en la selección en base a uno u otro tipo de representación pueden esclarecer no sólo la etapa o nivel de procesamiento de la información visual en la cual ocurre la selección, sino que puede reformular incluso los propios modelos teóricos.

Por una parte, existen demostraciones de que varias áreas corticales y subcorticales participan en la atención espacial, correspondiendo a la corteza parietal posterior el papel más significativo. Lesiones en esta región (particularmente en el hemisferio derecho) conducen a un trastorno neuropsicológico conocido como hemi-inatención, consistente en que los pacientes que lo padecen no prestan atención a los estímulos presentes en el hemicampo visual contralateral a la lesión.

En la medida en que los pacientes con hemi-inatención se recuperan de su trastorno, muestran otra alteración conocida como extinción, consistente en la incapacidad para atender un estímulo en el hemicampo visual afectado cuando se presenta de manera simultánea con otro estímulo en el hemicampo visual conservado. La extinción opera como un tipo particular de hemi-inatención, provocada por la competencia de un estímulo simultáneo localizado en el hemicampo ipsilateral a la lesión.

Estos pacientes han sido estudiados utilizando diseños de pre-aviso espacial como los ya descritos. Se han observado asimetrías en el costo debido al pre-aviso no válido, obteniéndose peores desempeños cuando se pre-avisa la ocurrencia del estímulo en el hemicampo conservado y éste en realidad se presenta en el hemicampo ignorado (revisado en Vecera y Luck, en prensa).

Estudios psicofisiológicos en monos, basados en el registro intracraneal de la actividad eléctrica unitaria de neuronas del lóbulo parietal, parecen confirmar el papel de esta área en la atención espacial. Las neuronas del área intraparietal lateral (IPL) tienen campos receptivos organizados topográficamente que responden a la estimulación visual. Cuando se produce un movimiento ocular de una localización espacial a otra, el campo receptivo de una neurona del área IPL también cambia a una nueva localización. Sin embargo, breve tiempo antes de que el movimiento ocular ocurra (aproximadamente 400 ms), ya el campo receptivo de la neurona responde ante estímulos presentados en la localización que le corresponderá luego, anticipando el movimiento ocular (revisado en Vecera y Luck, en prensa).

Utilizando la técnica de los Potenciales Relacionados a Eventos (PRE) también se han obtenido evidencias de la atención espacial. La presentación de estímulos visuales comúnmente provoca dos componentes tempranos (entre los 100 y 200 ms posteriores a la presentación) conocidos como P1 y N1. La modulación atencional de ambos componentes se ha estudiado en distintas tareas de selección espacial: tareas de atención sostenida sobre una localización espacial (Mangun y Hillyard, 1990;1995; Mangun, 1995; Eason, Harter y White, 1969; Van Voorhis y Hillyard, 1977; Neville y Lawson, 1987), tareas de pre-aviso espacial (Mangun y Hillyard, 1991; Eimer, 1993; 1994; Luck, Hillyard, Mouloua, Woldorff, Clark y Hawkins, 1994), y tareas de búsqueda visual (Luck, Fan y Hillyard, 1993).

Ambos componentes exógenos, cuya generación se estima en las áreas visuales extraestriadas, son modulados (se reduce su amplitud) cuando los estímulos son presentados en una localización no atendida. Al mismo tiempo, los componentes P1 y N1 relacionados con la presentación de estímulos irrelevantes en una localización atendida no pueden ser suprimidos (Heinze, Luck, Münte, Gos, Mangun y Hillyard, 1994).

En tareas que requieren una selección basada no en el espacio sino en otro atributo visual (por ej.: el color), no se observan diferencias entre los componentes P1 y N1 relacionados con los estímulos atendidos y no atendidos, sino una negatividad endógena, más lenta y más tardía ('negatividad de selección', revisado en Näätänen, 1992), superpuesta a los componentes P1 y N1 asociados a los estímulos del atributo atendido (Aine y Harter, 1986; Hillyard y Münte, 1984; Anllo-Vento y Hillyard, 1996). Esta 'negatividad de selección', relacionada con un procesamiento adicional de los estímulos seleccionados, se reduce considerablemente cuando los estímulos del atributo atendido se presentan en una localización no atendida (Hillyard y Münte, 1984).

La interpretación funcional de estos resultados sugiere una relación jerárquica entre los criterios de selección, otorgándosele al espacio un papel primario. Se asume que la magnitud de los componentes P1 y N1 refleja el grado de análisis sensorial y perceptual. Los estímulos presentados en localizaciones no atendidas no se procesan profundamente porque su procesamiento es inhibido tempranamente; los estímulos presentados en la localización atendida son procesados con profundidad, pudiéndose llevar a cabo entonces una selección basada en un atributo visual diferente.

El mismo diseño experimental ha sido modificado para registrar intracranealmente en monos la actividad unitaria de neuronas en la corteza visual. Los resultados obtenidos (Luck, Chelazzi, Hillyard y Desimone, 1997) fueron similares: no se encontraron efectos atencionales en la respuesta de las neuronas de V1 pero sí en las de V4, donde estímulos presentados en localizaciones atendidas evocaron mayores tasas de descargas eléctricas. Este efecto fue tan temprano como a los 60 ms posteriores a la presentación del estímulo, una latencia relativamente coincidente con la del comienzo del componente P1 en los estudios de PRE.

La respuesta de una neurona ante un estímulo es atenuada cuando la atención se dirige a otra localización dentro de su campo receptivo (para una revisión, ver Desimone y Duncan, 1995), lo cual puede ser interpretado funcionalmente como la acción de un filtro temprano que no permite (o atenúa) el procesamiento de los estímulos que ocurren en localizaciones diferentes a la seleccionada.

Por otra parte, al igual que en el caso de la selección espacial, existen estudios neuropsicológicos de pacientes con hemi-inatención derivada de lesiones en el lóbulo parietal. Algunos pacientes con daño en el lóbulo parietal derecho (hemi-inatención izquierda) no sólo ignoran el hemicampo visual izquierdo (hemi-inatención espacial), sino, además, el lado izquierdo de un objeto localizado en el hemicampo visual conservado (hemi-inatención de objeto).

Lo anterior se ha hecho evidente en tareas en las cuales los pacientes debieron discriminar si dos objetos eran iguales o diferentes. Si ambos objetos diferían en su lado izquierdo pero eran idénticos en su lado derecho, los sujetos los reportaban incorrectamente como iguales (revisado en Vecera y Luck, en prensa). Con el objetivo de determinar si la hemi-inatención de objetos se basa en coordenadas espaciales abstractas o centradas en el propio objeto, ambos objetos fueron rotados 45 grados, de forma tal que el rasgo distintivo se situara en la mitad espacial del objeto supuestamente conservada. La incapacidad para reportar la diferencia se mantuvo, evidenciando que la hemi-inatención de objetos sigue el eje propio del objeto.

Del mismo modo, pacientes con lesiones difusas en las cortezas occipitales (áreas visuales tempranas) presentan un tipo de agnosia a la percepción de formas visuales. Aún cuando conservan intactos la agudeza visual, el procesamiento del color, etc., son incapaces de organizar perceptualmente la escena. Estos pacientes mantienen la atención espacial pero no pueden efectuar una selección orientada a los objetos (revisado en Vecera y Luck, en prensa).

La atención basada en objetos también ha sido investigada mediante técnicas psicofisiológicas. Si bien han sido escasos los intentos de hallar evidencias de la modulación atencional de los PRE basada en los objetos, así como pobres sus resultados, sí se han obtenido datos que confirman efectos atencionales de este tipo en registros intracraneales realizados en primates.

Si dos objetos se movían dentro del campo receptivo de una neurona, uno de ellos en la dirección preferida de la misma (aquella que provoca la mayor cantidad de respuesta) y el otro en la antipreferida, el patrón de actividad eléctrica de la célula cambiaba en función del objeto atendido. Si el mono atendía al objeto que se desplazaba en la dirección preferida de la célula la respuesta era máxima. Si atendía al que se movía en la dirección antipreferida, entonces se inhibía la respuesta a pesar de existir otro objeto (ignorado) dentro del mismo campo receptivo desplazándose en la dirección preferida (Treue y Maunsell, 1996).

La percepción visual frecuentemente se concibe como una construcción serial y ascendente en distintos niveles de complejidad y abstracción de las representaciones (Verghese y Stone, 1996; Marr, 1982; Vecera y Farah, 1994). Se estima entonces que la selección atencional orientada a los objetos ocurre en estadios más tardíos del procesamiento que la selección espacial, en áreas de integración de la vía visual posteriores al procesamiento de los rasgos elementales.

Sin embargo, otros estudios de registros intracraneales en primates de la actividad eléctrica de poblaciones de neuronas en la corteza visual primaria (V1) han aportado evidencias de una temprana modulación atencional orientada a los objetos. Cuando se atiende a uno de dos objetos presentes en una imagen, se incrementa el nivel de descarga en aquellas neuronas cuyos campos receptivos procesan atributos del objeto atendido (revisado en Vecera y Luck, en prensa).

Explicaciones alternativas a las evidencias de la atención orientada a los objetos

A pesar de las numerosas evidencias experimentales anteriormente examinadas en favor de la atención orientada a los objetos, es necesario destacar que muchas de ellas han sido cuestionadas. Los resultados obtenidos en algunos de los diseños experimentales descritos no han sido replicados en estudios posteriores (por ej.: Kramer, Tham y Yeh, 1991, y Berry y Klein, 1993, no encontraron efectos de agrupamiento a partir del movimiento). Sin embargo, generalmente no son puestos en duda los resultados, sino la interpretación que se ha hecho de dichos resultados basada en una selección orientada a los objetos.

Uno de los problemas fundamentales que ha debido enfrentar esta perspectiva es la existencia de diversas explicaciones alternativas que, sin basarse en los objetos, pueden explicar muchos de los datos antes considerados como demostraciones. Tal es el caso de los experimentos que utilizan objetos estáticos superpuestos, uno de los cuales pudiera ser seleccionado no en base a una representación de alto nivel de integración o a una conjunción de atributos perceptuales, sino mediante un filtraje sensorial de bajo nivel sobre la base de algún rasgo elemental.

Así, se ha planteado que en los experimentos desarrollados por Duncan (1984) la información correspondiente al rectángulo y la línea juntos está más ampliamente distribuida que la correspondiente sólo a la línea (Kramer y Jacobson, 1991), implicando posiblemente focos atencionales de diferente tamaño. También se ha propuesto (Watt, 1988) que ambos objetos poseen diversos contenidos de frecuencia espacial; por lo que los costos de ejecución, supuestamente debidos a la competencia de los objetos por la atención, pueden explicarse por la necesidad de ampliar el procesamiento a un rango mayor de frecuencias espaciales.

Otra explicación alternativa de estos resultados, basada en una selección espacial tridimensional, sugiere que los objetos superpuestos se perciben en diferentes planos de profundidad (Lavie y Driver, 1996). Por lo que la interferencia puede originarse no en la dificultad de atender a dos objetos simultáneamente, sino a dos planos diferentes.

Por otra parte, la proposición de que la selección de objetos, tal y como opera en dicho experimento, es espacialmente invariante (Vecera y Farah, 1994), ha sido bastante discutida (Kramer, Weber y Watson, 1997; Vecera, 1997; Lavie y Driver, 1996). Se han formulado modelos que plantean que la organización perceptual guía la atención, pero lo hace definiendo las localizaciones ocupadas por los objetos. Por tanto, se selecciona entre estas localizaciones, y no entre representaciones de alto nivel (Kramer, Weber y Watson, 1997; Vecera y Farah, 1994).

Desde este enfoque espacial modificado se postula que las localizaciones no se seleccionan a partir de su distancia desde un punto en el espacio (como en los modelos espaciales clásicos), sino porque pertenecen a un determinado grupo perceptual. La atención puede adaptarse flexiblemente a la silueta de un objeto a partir de una representación interna del espacio visual.

Por último, los principios básicos de la selección de objetos en su versión clásica también han sido atacados desde otros modelos más recientes de atención orientada a los objetos. En primer lugar, se propone que varios objetos (hasta cuatro o cinco) pueden ser atendidos simultáneamente (Pylyshyn y Storm, 1988; Pylyshyn, 2000; Yantis, 1992), si pueden a su vez integrarse en una representación superior.

En segundo lugar, se sugiere que la selección atencional de un objeto no tiene que ser necesariamente uniforme a través de todas sus partes o localizaciones internas (Egly, Driver, y Rafal, 1994; Lavie y Driver, 1996; Behrmann, Zemel y Mozer, 1998; Vecera, Behrmann y McGoldrick, 2000), distinguiendo el espacio intra e interobjeto. Como evidencia fisiológica de lo anterior, se ha demostrado (revisado en Vecera y Luck, en prensa) que las neuronas del campo suplementario del ojo, localizadas en la superficie dorsomedial de los lóbulos frontales, codifican selectivamente posiciones espaciales específicas dentro de un objeto.

Transparent motion and object-based attention.

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Resumen:

La dificultad para procesar dos estímulos al mismo tiempo se incrementa con la separación espacial de los mismos. Por tanto, para demostrar la existencia de una interferencia debida a la división de la atención entre objetos diferentes es necesario controlar las posibles contribuciones de la separación espacial entre los mismos. Duncan (1984), utilizando objetos superpuestos, nos muestra que juzgar dos atributos de un mismo objeto es más preciso que juzgar dos atributos de objetos diferentes. Sin embargo, estos resultados han sido criticados a partir de la existencia de diferencias en el contenido de frecuencia espacial a procesar entre ambas condiciones. En este trabajo estudiamos el movimiento transparente, definido por dos conjuntos de puntos de diferente color entremezclados en una misma región del espacio, cuyas propiedades de frecuencia espacial coinciden. Cada conjunto se mueve en una dirección diferente escogida aleatoriamente. Encontramos que los juicios simultáneos de velocidad y dirección son más precisos cuando se refieren a un sólo conjunto que a diferentes conjuntos. Además, la discriminación simultánea de la dirección del movimiento de ambos conjuntos es más difícil que la discriminación de la dirección del movimiento de un solo conjunto, dificultad que se incrementa a medida que los movimientos duran menos tiempo. Concluimos, consistentemente con la perspectiva de la atención basada en los objetos, que el agrupamiento perceptual a partir del "destino común' ejerce una influencia más fuerte que la proximidad espacial. Por último, se discuten evidencias de que este tipo de selección atencional orientada a los objetos opera en estadios tempranos de la visión.

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Brief Article

Transparent motion and object-based attention

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Abstract

The difficulty in processing two stimuli at once increases with their separation. Therefore to demonstrate constraints in dividing attention between objects, the effects of their spatial separation must be controlled. Duncan used superimposed objects to achieve this, and showed that judging two attributes is more accurate if they concern one object than if they concern two objects (Duncan, J. 1984. Journal of Experimental Psychology: General, 113, 501–517). However, critics claim that differences in the spatial or spatial-frequency extent of attention exist between these conditions. We studied transparent motion defined by two sets of differently colored dots that were interspersed in the same region of space, and matched in spatial and spatial frequency properties. Each set moved in a distinct and randomly chosen direction. We found that simultaneous judgments of speed and direction were more accurate when they concerned only one set than when they concerned different sets. Furthermore, appraisal of the directions taken by two sets of dots is more difficult than judging direction for only one set, a difficulty that increases for briefer motion. We conclude that perceptual grouping by common fate exerted a more powerful constraint than spatial proximity, a result consistent with object-based attention. Evidence that this type of object-based attention operates at early stages of vision is examined. © 1998 Elsevier Science B.V. All rights reserved

Keywords: Attention; Transparent motion; Surfaces; Visual object

Visual attention has been conceived as either selecting spatial locations, or as selecting perceptual objects (Duncan, 1984; Egeth and Yantis, 1997). The two types of mechanism should be reflected by different constraints in dividing attention. In many experiments, the ability to divide attention between two stimuli is severely curtailed if their spatial separation is increased (Hoffman and Nelson, 1981; Hoffman et al., 1983). This has been considered a hallmark of spatially-based mechanisms of attention (Lavie and Driver, 1996). A similar dependence of attention distribution on perceptual organization would be expected for object-based mechan-

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isms, but a convincing demonstration would require appropriate controls for any contribution from the spatial distribution of the stimuli.

One bid to control for proximity has been to use objects that have been graphically superimposed so that both fall within the focus of attention (Neisser and Becklen, 1975; Rock and Gutman, 1981). Correspondingly, Duncan (1984) employed a small box with a superimposed line, each object with two attributes that could have one of two values for a given trial. He found that two judgments concerning only one of the objects were just as accurate as single judgment. In contrast, interference was found when the two judgments concerned different objects, which is consistent with object-based constraints on the division of attention. Vecera and Farah (1994) and Kramer et al. (1997) have replicated this result.

However, alternative explanations have been proposed for these experiments. It has been pointed out that the information about both the box and the line is more widely distributed than for the line alone (Kramer and Jacobson, 1991). A related observation by Watt (1988) is that Duncan's two objects could have a different spatial frequency content. Therefore, the divided-attention costs could reflect a different distribution of resources in space, or among spatial frequencies (see also Shulman and Wilson, 1987) instead of object-based constraints.

In the present study divided-attention was examined with transparent motion, which offers an ideal experimental opportunity to confront the objections to object-based accounts just examined. Transparent motion can be created when two sets of rigidly dots transverse the same region of visual space, each moving in a different direction (Andersen and Wüestefeld, 1993; Qian et al., 1994). This corresponds to the perception of two transparent surfaces sliding across each other. Each surface is an 'object' on which (in principle) attention can be selectively focused, or shared with the other surface.

There are several reasons why transparent motion is useful to examine object-based attention. First, the motion of the two sets of dots can be defined so they are spatially interspersed and transverse the same region of visual space. With an adequate dot density, this would make selective effects based on space very improbable. Second, the relative positions of the dots within each set can be drawn from the same probability distribution for both sets. Thus, any difference in spatial frequency between the images corresponding to each set can be minimized. Moreover, if new positions are randomly selected for each trial, no systematic differences in frequency content can be associated with either set. Third, exactly the same tasks can be used to measure attention for the two surfaces defined by transparent motion, avoiding the reproach that focused and divided-attention conditions (one vs. two objects) involve fundamentally different processes (for criticism of previous work on this basis see Lavie and Driver, 1996).

The present study demonstrates that attention can be selectively focused on one surface in transparent motion, with an advantage for this condition over attention divided between two surfaces. This indicates that effects of perceptual grouping by common fate on divided-attention can override spatial proximity (between neighboring dots). This provides clear evidence for object-based constraints not subject to the alternative interpretations reviewed above.

In the first experiment the logic developed by Duncan (1984) was adapted for use with transparent motion. In one condition, the participants were required to judge at once the speed and the direction of motion for one surface, whereas in the other condition they were required to judge the speed of one surface and at the same time the direction of motion of another (superimposed) surface. These two conditions were equivalent in the area of visual space over which the relevant information was deployed, and exactly matched in the number and nature of the perceptual discriminations involved. If there are object-based attentional limitations, performance in the two-surface condition should be inferior to the one-surface condition.

Eight university graduates (four females and four males, of which six were right handed, and aged from 26 to 30 years) participated in the first experiment as volunteers. All the subjects had normal vision. Due to the difficulty of the task, potential subjects first practiced and were replaced if accurate performance was not obtained.

The stimuli consisted of two spatially interspersed sets of 50 dots each, one colored blue and the other a roughly equiluminant yellow which were continuously present during the session. During each trial the two sets of dots were linearly displaced for a period of 1000 ms, each moving in a different dominant direction. The moving dots were presented within a 'virtual square aperture'. Dot lifetime was equivalent to trial duration. If a dot passed the border of the imaginary figure, it was wrapped around to an opposite but symmetrical position. Thus the spatial overlap of the two sets of dots was maintained during each trial. Eight directions of motion were used; starting at 0 deg and with 45 deg steps (i.e. the cardinal and diagonal directions). Within each set, displacements were partially coherent, with 25 dots moving in a common direction, and the other dots moving in a randomly selected direction out of the seven not employed by the coherent subset. This partially-coherent motion was employed to compel attention to the complete ensemble, instead of a focus on individual dots.

Experiments took place in a room with dim illumination while the participants sat in a comfortable chair with a headrest. At the beginning of each block the participants were instructed on which combination of judgments they should perform. After fixating the center of the swarm of dots, participants initiated each trial (and stimulus motion began after a 500 ms delay) by pressing the space-bar of the computer keyboard. Fixation at the center was required until stimulus motion offset. On each trial one speed and one direction judgment (in that order) were reported via the computer keyboard. Accuracy was emphasized over response speed. Incorrect responses were signaled by a 500 ms beep on the computer loudspeaker.

Four blocks, each comprised of 60 trials, were presented in one session. The required distribution of attention was instructed before each block. Each block represented a different combination of direction and speed judgments (direction and speed of the blue dots; direction and speed of the yellow dots; direction of the blue dots and speed of the yellow dots; direction of the yellow dots and speed of the blue dots). The order in which the blocks were presented was counterbalanced over participants. Subjects rested between blocks for several minutes.

The accuracy of the discriminations is shown in Fig. 1. The percentage of correct responses was submitted to a repeated measure analysis of variance (rm-ANOVA).

Since the main effect and all the interactions related to the color of the surface were not significant, this factor will be ignored below. The speed-discrimination task was less accurate than the direction discrimination task, $F(1,7) = 5.29$, $P < 0.045$. Accuracy in both tasks decreased in the two-surface condition as compared to the one-surface condition, $F(1,7) = 21.5$, $P < 0.0024$. For speed-discriminations, accuracy dropped from about 72% in the one-surface condition to about 67% in the two-surface condition, an effect that did not reach significance. For direction-discriminations, accuracy dropped from about 85% in the one-surface condition, to about 72% in the two-surface condition, $F(1,7) = 20.3$, $P < 0.0028$. This pattern was reflected in a significant interaction of attribute and number-of-surface, $F(1,7) = 6.96$, $P < 0.033$.

Speed discrimination task was harder to judge than direction despite that being reported first. In previous studies of divided-attention there is a clear advantage for the first reported dimension (Duncan, 1984; Duncan, 1993a; Duncan, 1993b). The disadvantage of the speed judgment in our experiment is perhaps related to the small difference in magnitude between the two speed conditions employed (about 0.3 deg/s). The greater difficulty of the speed discrimination judgment may have induced the

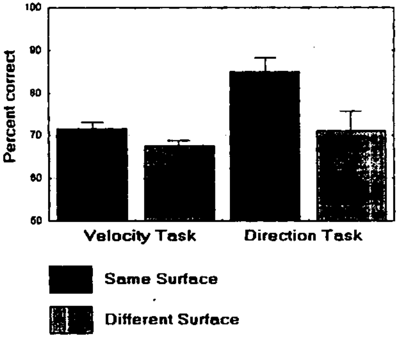

Fig. 1. Percent correct scores in the first experiment for the direction and velocity tasks as a function of the number-of-surfaces attended. Note that performance was lower in the divided-attention conditions. Each data point corresponds to the mean of eight subjects. The whiskers represent 1 SE. Methods: visual stimuli were presented on a sVGA monitor (frame rate 60 Hz, non-interlaced), placed at about 70 cm from the subjects, and controlled by a 33 mHz 486-DX2 microcomputer. The background was black. Each dot was 1 pixel in size (about 4.6 arcmin wide and high). Dots were painted in randomly selected locations (x and y where drawn from uniform distributions) within an imaginary square with sides of about 4.54 deg. The average dot density in each set was about 2.4/deg^2. Two speeds of dot motion were used, 1.2 or 1.5 deg/s randomly selected for each surface on each trial. Apparent motion was achieved by continuous redefinition of the position of the dots, in synchrony with the video signal. The speed of motion (slow or fast) was indicated on the F1 and F2 keys. Direction of motion was indicated on the arrow keys (and intermediate keys: Home, PageUp, PageDown and End) of the numerical-pad of the computer keyboard.

subjects to place higher priority on this part of their task. This, together with the fact that it was reported first, would explain the relative insensitivity of the speed discrimination to the number of surfaces implicated in the task.

Despite that in all conditions exactly the same pair of discriminations (direction and speed judgments) were required, performance on the direction discrimination task was clearly more efficient when the two tasks concerned one surface than when they concerned two surfaces. This is a replication (and extension to motion-related properties) of the results reported by Duncan (1984, 1993a,b) and Vecera and Farah (1994). In particular our results fit well with the findings of Duncan and Nimmo-Smith (1996), who report interference between motion-direction judgments concerning two spatially-separate sets of dots (Experiment 3). That study found that attention can not be directed towards two sources of motion information at the same time without performance costs. The present experiment replicates this finding, but by using superimposed transparent stimuli, avoids the confounding of space with objects.

The results of the first experiment support the contention that attention cannot be divided efficiently between two superimposed surfaces defined by transparent motion. A related prediction was examined in the second experiment. Appraisal of the direction in which one transparent surface moves should interfere with the same judgment about another superimposed surface, if there are object-based constraints to the division of attention. The effect should be apparent in superior performance for a focused-attention task (where responses are required to only one surface), as compared to a divided-attention task (where responses are required to dots from the two surfaces). Additionally in the second experiment we examined the effect of varying the time during which stimulus motion information was available.

The methods of the second experiment were identical to those of the first except as follows. Ten subjects participated as volunteers (five females, five males, of which nine were right handed). The two sets of 100 dots were colored red and green respectively, with intensities matched by heterochromatic flicker photometry for each participant. A fixation point was placed at the center of the screen. A circular 'virtual aperture' was used. The following durations of the stimulus motion were used: 150, 500 and 1000 ms.

An important deviation from the first experiment was the use of a rotational baseline motion, 700 ms before and 700 ms after the translation motion discriminanda. During the baseline the two sets of dots (now red and green) rotated around the fixation point in opposite directions. This rotational baseline served a dual purpose. The first baseline period allowed time for an initial segregation of the two transparent surfaces. This was important in assessing performance for the 150 ms stimulus duration. Uncertainty about scene segmentation could be confounded with interference in divided-attention for this very brief event. The final rotational motion served to mask the stimulus motion, (see Valdes-Sosa et al., 1998), and therefore limited the temporal availability of the stimulus information.

Within a block, attention was directed to either one surface (in the focused-attention blocks), or to both (in the divided-attention blocks). In the divided-attention block one surface was treated as primary whereas the other surface was considered as secondary. The instructions emphasized that maximum priority should be allocated to the primary surface, with the goal of restricting performance decrements to the secondary task. Responses to the primary surface were required first.

The color of the fixation point indicated for each block, either the attended surface (in the focused-attention conditions), or the primary surface (in the divided-attention conditions), a specification that was held constant for the duration of the block. Events in each trial, which were self-paced, were sequenced as follows: a 700 ms baseline rotation; the stimulus motion; and then a 700 ms baseline. After the offset of the final baseline motion, a request to report the direction of motion for one surface was printed above the dots, with the message 'red' or 'green' (in letters of the corresponding color). One message was used for the focused-attention blocks or two consecutive messages for the divided-attention blocks.

Each participant was presented with four blocks, of 99 trials each, in one session. The blocks were attend-red, attend-green, attend-both with green as primary; attend-both with red as primary. The order in which the blocks were presented was counterbalanced over participants. Subjects rested between blocks for several minutes. The percentage of correct responses was submitted to a rm-ANOVA using three factors: response-type (with three levels, one from the focused-attention blocks, and primary and secondary from the divided-attention block); stimulus-motion duration (150, 500 and 1000 ms); and color of the surface (red and green). The Greenhouse–Geisser correction was used, and epsilon values are reported. Since the main effect (and all the interactions) related to the color of the surface were not significant, this factor will be ignored below.

Fig. 2 shows the mean percentage of correct responses as a function of stimulus motion duration and trial-type. A highly significant effect of trial-type was observed, $F(2,18) = 152.5, P < 0.0001, \epsilon = 0.78$, with the most accurate responses from trials in the focused-attention blocks. Primary responses did not differ significantly in accuracy from focused-attention responses. However, percent correct was significantly smaller for the secondary responses than for the other responses, $F(2,18) = 9.5, P < 0.002$. Percent correct increased monotonically as stimulus-motion duration increased, an effect that was highly significant, $F(2,18) = 165.4, P < 0.0001, \epsilon = 0.86$.

The interaction of trial-type and stimulus-motion duration was also highly significant, $F(4,36) = 6.13, P < 0.0043, \epsilon = 0.65$. This interaction reflected the large effect of stimulus duration on responses to the secondary surface (a drop of about 40% correct as stimuli were shortened from 1000 to 150 ms), in the face of more moderate effects on the accuracy of focused-attention and primary surface responses (which decreased in about 20% correct for the same variation of stimulus duration).

A significant decrease of accuracy for the direction discrimination was observed for the secondary surface in the divided-attention task, as compared with the corresponding primary task, or the focused-attention task. These results indicate that it is not possible to attend efficiently to two surfaces at the same time, and that as the interference is augmented by reducing the time during which stimulus information is

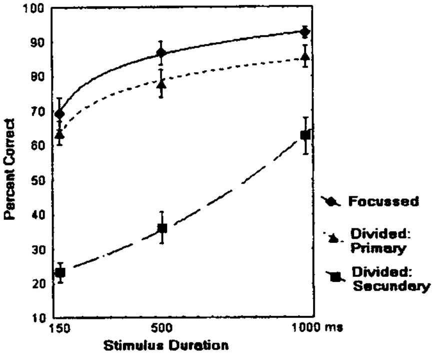

Fig. 2. Percent correct as a function of distribution of attention and duration of motion in the second experiment. In the focused-attention condition, direction of motion was reported for only one surface. The other two curves were obtained from the divided-attention condition, in which attention was directed towards both surfaces, but a higher priority was given to the primary as compared to the secondary surface. Each data point corresponds to the mean of 10 subjects. The whiskers represent 1 SE. Curves fitting the means for the focused and primary conditions are logarithmic regressions, whereas the curve for the secondary condition is an exponential regression. Methods: each set consisted of 100 dots that were placed within an imaginary circle with a diameter of about 6.9 deg and that was centered on the fixation point, which resulted in a dot density for each set of about $2.7/\text{deg}^2$. The fixation point was a circle of 28 arcmin diameter. During baselines the red dots rotated in clockwise direction around the fixation point, while at the same time the green dots rotated in anti-clockwise sense. The speed of rotation was about 2.3 deg/s. The speed of the translation motion was about 3 deg/s. The coherence of the motion was 60%. Direction of motion was reported via the keyboard as in the first experiment.

available. Since the performance decrement is essentially limited to the secondary task (except perhaps for the shortest intervals), very effective perceptual filtering of the unattended surface is suggested.

Both experiments indicate that dividing attention between the two components of a transparent motion leads to severe performance costs. These results are incompatible with several types of attentional mechanisms that have been previously proposed as alternatives to object-based selection. Given the spatial distribution of the dots comprising the perceived surfaces, space-based models do not fit the data. The dots were commingled, at a relatively high density, within the same region of visual space. The classical spotlight metaphor does not allow selective attention to one set of dots interspersed among another set of dots. In this metaphor, all input within the focus of attention must be selected together. Moreover since the spatial extent and distribution associated with both sets were equivalent, selection based on spatial frequencies was not probable (see also Valdes-Sosa et al., submitted, for future evidence against this possibility).

Modified spatial accounts, such as the grouped array hypothesis (Vecera and Farah, 1994; Kramer et al., 1997) would also have trouble accommodating the results. In contrast with a spotlight, attention can be flexibly directed to all locations occupied by an object according to the grouped array account. In other words, the focus of attention can 'silhouette' the object. The strongest support for grouped arrays (Lavie and Driver, 1996) is the finding that spatial proximity to attended objects facilitates processing, and the fact that irrelevant probes placed at locations previously occupied by an attended object are processed more efficiently than probes placed elsewhere. The former argument is belied by the large interference found in the present study when attention was divided between neighboring dots that belong to different perceptual groups. The latter argument is confuted by the fact that the dots were continuously in motion with elements from different sets crossing over each other. Thus attended and ignored elements frequently shared the same (or nearby) locations.

It could be argued that the subjects perceived the two sets of dots as surfaces placed at different depth planes. Therefore the difficulty in dividing attention could reflect spatial attentional constraints in three-dimensional space, a possibility demonstrated in other studies (e.g. Nakayama and Silverman, 1986; Andersen, 1990; but see Ghirardelli and Folk, 1996). However the subjects reported that they perceived the displays as quite flat, and that the subjective separation of the two 'surfaces' in three-dimensional space was very small. Results from a companion study (Valdes-Sosa et al., submitted), using stimuli and tasks identical to those reported here, also make this explanation unlikely. In that study, the two sets of dots were assigned different binocular disparities that elicited a clear subjective separation in depth, but were still close enough to be interpreted as one object when the dots were static. No costs were found for dividing attention between two static surfaces separated only by subjective depth, whereas dividing attention between two surfaces segmented by relative motion lead to large impairments in performance

Furthermore, discrimination-based models of visual attention cannot explain the results (Treisman, 1969; Allport, 1971). In these models, attentional interference originates when the same perceptual analyzers are demanded by concurrent discriminations. Also, in discrimination-based models, higher between-attribute similarity should generate more attentional interference. In the first experiment, in spite of the fact that same the perceptual analyzers were required for the one- and two-surface conditions, performance was lower when attention had to be divided between two objects. Furthermore, speed and direction are closely related attributes tied to stimulus motion and both are coded by neurons in the same specialized areas of the visual system (reviewed in Snowden, 1994 and also Logothetis, 1994). Contrary to the predictions of a discrimination-based model, very efficient performance was possible if the two judgments concerned the same surface. Duncan (1993a,b) has reached similar conclusions. He found that interference depended very little on the similarity of two discriminations, but very much on whether they concerned the same object.

An important additional question is how early in vision does this attentional selection take place. A clue to this may be found in the large interaction found between motion-duration and reported surface (primary or secondary) in the dual task situation. Whereas shortening the motion affected the primary and focused-attention tasks very little, the same manipulation lead to a large interference for the secondary task. Early attentional selection is identified with competition for limited perceptual resources (c.f. Ben-Av et al., 1992). The fact that reduced availability of the visual input increased the dual task interference strongly suggests early selection (Norman and Bobrow, 1975). This conclusion is reinforced by a study with event related potentials (Valdes-Sosa et al., 1998), showing that the type of attention examined in this report is associated with strong suppression of the P1 and N1 elicited by motion-onsets from the unattended set of dots. These electrical brain responses are thought to originate in early extrastriate cortices (Schlykowa et al., 1993; Kubová et al., 1995; Anderson et al., 1996; Patzwahl et al., 1996). Additionally, Lankheet and Verstraten (1995) have shown that attention to one component of transparent motion can eliminate its contribution to the motion aftereffect. Taken together, these observations suggest that the object-based effects evidenced in this study could arise at very early stages of vision.

We conclude that attention can be selectively directed to one component of transparent motion, and that dividing attention between the two components is associated with performance costs. This offers strong evidence for object-based selection that is not subject to the criticisms previously directed against studies of object-based attention. The paradigm offers a situation in which perceptual grouping clearly overrides spatial proximity and offers interesting opportunities for further research.

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Attention to object-files defined by transparent motion.

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Resumen:

Se realizaron cuatro experimentos para estudiar la división de la atención entre dos superficies transparentes superpuestas. Las superficies se crearon rotando en sentidos opuestos dos conjuntos de puntos entremezclados, siendo ambos conjuntos de diferente color. Los dos eventos a discriminar consistían en cambios breves de la dirección del movimiento que ocurrían serialmente. Si los dos eventos afectaban una misma superficie, se discriminaban con precisión en todas las condiciones. Si el primer evento ocurría en una superficie y el segundo evento ocurría en la otra superficie, este último era discriminado con escasa precisión si el tiempo transcurrido entre ambos eventos era inferior a los 600 ms. Esta interferencia refleja la dificultad para cambiar la atención entre superficies. Varios controles indican que esta limitante no puede explicarse por los mecanismos espaciales tradicionales (ni siquiera a partir de una representación espacial tridimensional). Un hallazgo novedoso resultó ser que esta interferencia es mayor entre estímulos espacialmente más próximos entre sí. Además, se descarta un filtraje basado en atributos sensoriales simples. Concluimos que los eventos fueron seleccionados atendiendo al 'archivo de objeto' al cual pertenecían. Sin embargo, la interferencia no se debe simplemente a una incapacidad para procesar dos objetos simultáneamente, también parece ser necesaria la proximidad espacial entre las señales de movimiento que no pueden ser generadas por la misma fuente.

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Attention to Object Files Defined by Transparent Motion

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Two interspersed and differently colored sets of dots were rotated in opposite directions and were perceived as superimposed transparent surfaces. Probes consisting of brief changes in dot motion direction were reported. Two probes affecting the same surface were discriminated accurately. The 2nd probe was discriminated poorly if it affected a surface different from the 1st and if the time between probes was less than 600 ms. This reflects a difficulty in switching attention rapidly between surfaces. Spatial proximity increased the interference. Controls were incompatible with traditional spatial mechanisms (2- or 3-dimensional) or with simple sensory filters. Instead, probes were apparently selected by object files. The interference is not simply due to an inability to process 2 objects at once but requires close spatial proximity of incompatible motion signals.

Two different views on how visual attention operates have competed during recent years. Attention has been conceived as selecting places or as selecting objects for processing (Egeth & Yantis, 1997). The two perspectives are not mutually exclusive and may concern different, but complementary, mechanisms. However, for any particular set of data the explanatory power of each view has been intensely debated. This is the case for experiments on divided attention (Lavie & Driver, 1996). In divided attention, multiple stimuli (typically placed at different locations) are processed. If the discriminations involved are sufficiently difficult (Duncan & Humphreys, 1989), this plurality will lead to a performance decrement compared to a one-stimulus condition. Does the interference arise because different sites are concerned, or because different objects in the scene are concerned?

Spatial Constraints on the Division of Attention

Selective visual attention has been frequently thought to reflect the distribution of processing resources among locations in an internal representation of visual space. The distribution is usually subject to geometric rules producing a unitary, compact, and convex two-dimensional locus of selection (Nakayama & He, 1995; Yantis, 1992). The locus has been likened to a spotlight (Posner, 1980), a zoom lens (C. W. Eriksen & St. James, 1986), or a gradient (Downing, 1988). In the simplest spatial models, there was no role for perceptual organization. This spatial mode of distributing attention entails several consequences for divided attention (reviewed by Lavie & Driver, 1996), two of which are labeled here as the *proximity benefit* and the *location inertia*. These properties have been considered hallmarks of spatially based mechanisms of attention.

Both these principles are nicely illustrated by a series of experiments by LaBerge and collaborators (LaBerge & Brown, 1989; LaBerge, Carlson, Williams, & Bunney, 1997). In these experiments attention was divided over time and space. They first cued a location and then presented there briefly a letter embedded amid distractors, which was followed by a second chain of symbols also containing a target letter. The distance between the two targets was varied. Speeded responses were required for certain pairs of targets. Responses were faster if the second target replaced the first at the same location and gradually slowed as the distance between the two was increased. This evinces location inertia, because a second target obtained benefits by occupying the location of a previous target. It also manifests proximity benefits (in the form of a gradient): As two stimuli are brought closer together, dividing attention between them becomes easier.

The more recent grouped-array account (Vecera & Farah, 1994) also uses spatially based mechanisms but acknowledges the role of perceptual organization. In this view, locations are selected not because they lie at a specified distance from some point in space (as in the classical variants) but because they belong to a perceptual group. Thus, a flexible attentional "beam" could follow the silhouette of an object within the internal representation of visual space. Although the classical spatial models and the grouped-array account disagree in the "how," they concur in the "what" of selection. By assuming that attention is directed to locations and not their content, they imply either proximity benefits or location inertia, and both effects have been used recently to distinguish between selection of higher order representations and selection of grouped arrays (Kramer, Weber, & Watson, 1997; Vecera & Farah, 1994).

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The Search for Object-Based Attention

In object-based models (Duncan, 1984) perceptual resources are allocated to higher level entities, previously created by preattentive processes of grouping and scene segmentation. The higher level entities can be objects (Duncan, 1984), perceptual groups (Duncan & Humphreys, 1989), or surfaces (He & Nakayama, 1995; Nakayama & He, 1995).

Most experiments on visual attention have been interpreted exclusively in terms of space-based mechanisms (reviewed by Theeuwes, 1993; Treisman, 1988). However, in most experimental situations, different objects occupy distinct locations, and each object usually occupies a unique and continuous region of space. Therefore, space and objects are confounded. Either type of model could explain many of these experiments. Despite this, spatial mechanisms are usually invoked, and the burden of proof has been laid on proponents of object-based mechanisms.

As examined below, demonstrations of object-based attention have generated more controversy than their spatial counterparts. Attempts to dissociate selection by locations and selection by objects have used three different approaches (see the review by Egeth & Yantis, 1997).

In one line of work, two distinct objects are graphically superimposed to impede spatial selection. Early studies (Neisser & Becklen, 1975; Rock & Gutman, 1981) showed advantages in detecting or remembering events in attended, as compared with unattended, objects occupying the same region of visual space. Duncan (1984) further developed this approach. A box and a superimposed line were briefly displayed in his experiments. Two judgments concerning attributes of one object were performed simultaneously without accuracy loss (as compared with a single judgment), whereas interference was found when the two judgments concerned attributes from different objects. Because the stimuli were small, space-based mechanisms were considered unlikely and the two-object decrement was construed as being due to object-based constraints on the division of attention.

With the same stimuli and tasks, Vecera and Farah (1994) and Kramer et al. (1997) found a similar pattern of results. Vecera and Farah also showed that separating the two objects did not affect the cost of dividing attention across objects. They argued that this last result was consistent with selection from spatially invariant object representations. However, if the task was changed to the detection of dots presented on the same objects, clear spatial effects emerged, which may be due to the independence of the dot detection task from object layout (Lavie & Driver, 1996; Vecera & Farah, 1994).

The second tack in demonstrating object-based attention is to pit the influence of perceptual grouping against spatial proximity. Typical spatial effects in the *flanker* paradigm (B. A. Eriksen & Eriksen, 1974) can be outweighed by common motion of targets and distractors (Driver & Baylis, 1989) or by their grouping through color (Baylis & Driver, 1992; Bundesen & Pedersen, 1983; Kramer & Jacobson, 1991). Also, the usually slow search for conjunction of features (Treisman, 1988) can be speeded if the distractors are grouped together (and segregated from the target) by motion (Driver & McLeod, 1992; Duncan, 1995; McLeod, Driver, & Crisp, 1988; McLeod, Driver, Dienes, & Crisp, 1991). Furthermore, target elements are compared more efficiently when they belong to the same line rather than to two different lines, even if they are more separated in the former than the latter case (Lavie & Driver, 1996). Finally, the surface layout of a scene can also override spatial constraints in the distribution of attention (reviewed in Nakayama, He, & Shimojo, 1995).

The third approach in isolating object-based attention is to move the objects used as stimuli in order to dissociate them from a fixed location. This strategy was used by Tipper and collaborators (Tipper, Driver, & Weaver, 1991; Tipper, Weaver, Jerreat, & Burak, 1994), who found that certain inhibitory posteffects of attention (*inhibition of return*) are not exclusively spatially based (as originally thought) but are also object-based. The same scheme has been used by Kahneman, Treisman, and Gibbs (1992) to show object-based priming effects (based on tokens in contrast to types) and by Yantis (1992) in showing conceptually driven visual grouping effects on performance.

Doubts About Object-Based Attention

Despite the experimental reports just reviewed, the reality of object-based constraints on the division of attention has been disputed. One problem is that several alternative explanations have been proposed for many of the specific demonstrations of object-based attention. This is the case for experiments using superimposed static objects, one of which could perhaps be picked out by low-order sensory filters without recourse to object representations.

It has been noted that in the experiments reported by Duncan (1984) information about both the box and the line was more widely distributed than for the line alone (Kramer & Jacobson, 1991), possibly implying attentional windows of different sizes. Also, Watt (1988) suggested that Duncan's two objects could have different spatial frequency content. In this case, the costs of dividing attention could be due to the need to spread processing resources over a wider range of frequencies, and not to object-based attention (see also Shulman & Wilson, 1987).

A clever attempt to counter these objections (Baylis & Driver, 1993) used ambiguous displays, which can be perceived as containing either one or two objects. Comparing two features was faster when they were perceived as belonging to one rather than two objects. The relevant information was at identical locations for these two conditions. However, Lavie and Driver (1996) pointed out that the comparison within a single object could be based on its shape, which would not be possible for comparisons between two objects, thus revealing different degrees of intrinsic dependence on object organization for the two tasks.

An alternative, spatially based explanation of the two-object decrements in divided attention is that superimposed objects are perceived at different depth planes (see the note in Duncan, 1984, and the discussion by Lavie & Driver, 1996).[1] This interpretation is fueled by reports of costs related to shifts of attention, or division of attention, as a function of distance in depth within visual space (Andersen, 1990; Downing & Pinker, 1985; Nakayama & Silverman, 1986). Hence, the apparent difficulty in attending to two objects at the same time would really be due to a difficulty in attending to two depth planes.

Disagreement also exists on the nature of the representations involved in object-based constraints. According to the grouped-array account, although object structure guides attention, it is the locations and not higher order representations that are selected. Kramer et al. (1997), who used the same stimuli as Duncan (1984), took this position. They discounted the spatial invariance reported by Vecera and Farah (1994), while presenting evidence of location inertia (speeded responses) for postdisplay probes placed in the same visual regions as objects possessing two target attributes.

Finally, a different problem is that some of the posited object-based effects have not been replicated. For example, some of the motion-grouping effects that have been found in focused attention tasks were not reproduced (Berry & Klein, 1993; Kramer, Tham, & Yeh, 1991), and object-based inhibition of return was not found in one study (Müller & von Mühlenen, 1996). In summary, although the three different psychophysical approaches outlined above have generated evidence for object-based attention, several alternative explanations (that do not require higher order object representations) have been advanced and contradictory data have been reported.

Transparent Surfaces and Object-Based Attention

There is one well-studied situation in which all the approaches developed to isolate object-based attention can be combined. This is the case of motion transparency. Transparency arises when more than one surface lies along a line of sight. Transparent surfaces can be generated by stereopsis, when planes at different distances are defined by random-dot stereograms (Akerstrom & Todd, 1988; Weinshall, 1989), or by relative motion.

In transparent motion, more than one velocity field is simultaneously present in the same region of visual space. One example of this situation (which is used in this article) is when two sets of rigidly moving dots, each with a different direction, transverse the same area (e.g., Andersen & Wüestefeld, 1993; Qian, Andersen, & Adelson, 1994; Snowden, Treue, Erickson, & Andersen, 1991). This induces a vivid percept of two transparent surfaces sliding across each other. Transparent motion is not infrequent in nature. It arises when a discontinuous (and moving) object blocks another from view as when separate sheaves of grass are interposed before a predator or a fruit is hidden amid foliage. Shadows and specular reflections also create transparent motion (Qian et al., 1994).

Beyond considerations of the real-world importance of transparency, this phenomenon offers an ideal experimental opportunity to examine object-based attention. To begin with, surfaces have been considered the entities on which attentional selection operates (He & Nakayama, 1995) and can be considered as "objects" in a very elementary sense (a numerable "thing"; see Wolfe & Bennett, 1997). Of importance, the three approaches developed to isolate object-based from spatially based effects have an immediate application to transparent motion: (a) Because two surfaces defined by transparent motion are superimposed on the same region of visual space, spatial selection is hampered; (b) spatial proximity is pitted against perceptual grouping (by common fate) because elements belonging to different surfaces can be closer in space than elements from the same surface; and (c) because stimulus elements are not related to a fixed location (and even can be replaced by elements from the other surface), selection of locations is discouraged.

Previous work by Lankheet and Verstraten (1995) showed that when attention is directed toward one component of transparent motion, the contribution of the other component to the motion aftereffect is diminished. This provides indirect evidence that attention cannot be divided between two components of transparent motion. More recently (Valdes-Sosa, Cobo, & Pinilla, 1998), the logic developed by Duncan (1984) was applied to transparent surfaces, with the outcome that simultaneous judgments of direction and speed concerning one component of transparent motion were more accurate than the same two judgments when they were concerned with different components. In that study, interference was also found when the direction of motion had to be appraised for two components of transparent motion at the same time. This interference increased for briefer motion duration.

The Present Study

In the present study, the advantages offered by transparent motion are used to demonstrate object-based constraints on the division of visual attention, while avoiding the criticisms reviewed above. Evidence is presented that when attention is directed to events defined on one transparent surface, equivalent events on another superimposed surface are discriminated poorly. Several controls were designed to counter the alternative explanations raised against object-based selection.

This work builds on a previous study that used a sustained attention "filtering" task (Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998). In the present study, surfaces were generated by rotating two interspersed sets of dots (one set colored red and the other green) in opposite directions around fixation. Probes were defined as very brief changes in the direction in which dots from one surface were headed. On each trial two probes, separated by a delay, affected either the same surface or different surfaces. The participants were forewarned (cued) as to which surface would be affected by the first probe but were ignorant about which surface would be affected by the second probe. A superior performance in the one-surface compared with the two-surface conditions was

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[1] This explanation was also suggested by several reviewers.

considered evidence for surface- (object-) based constraints on the division of attention.

It is important to note that previous work with transparent motion has examined attention to fixed directions of motion (Lankheet & Verstraten, 1995; Valdes-Sosa, Cobo, & Pinilla, 1998). The probes used here allow exactly the same motion signals to be judged in attended and unattended surfaces. There is a formal similarity of our paradigm to the tasks developed by LaBerge and collaborators (LaBerge & Brown, 1989; LaBerge et al., 1997). In these tasks, attention is first cued toward a location and then engaged there by a target discrimination, after which performance triggered by a second target is measured as a function of the distance between the two targets. Here the role of locations is taken up by surfaces.

This study differs from many experiments on divided visual attention in that it used stimuli consisting of brief events that transform preexisting and relatively long-lasting objects. The more traditional abrupt-onset stimuli may tend to capture attention in a more automatic manner (Yantis, 1996). Also, previous research has usually involved form identification of stimuli in relatively sparse scenes. The displays used here, in which the elements belonging to each (spatially dense) perceptual group changed position and direction, can perhaps be best addressed with the notion of *object file* (Kahneman et al., 1992). Object files are conceived as temporary, episodic, and modifiable representations of entities (or tokens; see Kanwisher, 1987), which can be updated by new sensory input, thus allowing perception of continuity and unity in moving or changing objects. Each component of transparent motion can be conceived as an object file (or object token).

Experiment 1: Switching Attention Between Surfaces

In this experiment, the ability to divide attention between events affecting different object files was assessed with the transparent-motion paradigm outlined above. It is important to note that previous work comparing the accuracy of one-object and two-object judgments has used features that were present during the whole (brief) lifetime of the objects (Baylis & Driver, 1993; Duncan, 1984, 1993a, 1993b; Kramer et al., 1997; Lavie & Driver, 1996; Valdes-Sosa, Cobo, & Pinilla, 1998; Vecera & Farah, 1994). Does the disadvantage in performance for the two-object condition, found in all these studies, also extend to brief events separated in time that modify object files but do not destroy their identity? This question is not only interesting in the laboratory but (as stated above) is probably very relevant to real-world behavior, where identifying changes in the status of already detected objects is just as important as (or more important than) identifying abrupt-onset stimuli (cf. Neisser & Becklen, 1975).

Recent work suggests that attention lingers for hundreds of milliseconds on one object before it is free to process a second object presented separately in time (Duncan, Ward, & Shapiro, 1994; Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994; Ward, Duncan, & Shapiro, 1996; Ward, Duncan, & Shapiro, 1997). The time that attention is trapped on one object has been designated *attentional dwell time*. Although these studies used stimuli with abrupt onsets and offsets that did coexist in time, the long attentional dwell times found suggest that closely paced events affecting different object files cannot be processed without interference. In this experiment, the delay between probes was varied in order to estimate the time necessary to switch attention between the two surfaces defined by transparent motion.

Method

Participants. Personnel from the Cuban Center for Neuroscience, all university graduates, participated in this and the following experiments as volunteers. Their age range, sex distribution, and handedness are described in Table 1 (for this and subsequent experiments). All the participants had normal or corrected-to-normal visual acuity, reported no color vision abnormalities, and had no history of neurological disorders. Because the motion discrimination tasks used in the study were difficult, potential participants were first screened: They completed several blocks on the task for each experiment (these data were discarded) and were replaced if practice did not lead to accurate performance. The number of trials for the screening ranged from about 100 to 200. Participants with accuracy lower than 70% on first probes were rejected. The percentage of cases for which this happened in this and subsequent experiments is also indicated in Table 1.

Stimulus materials. Visual stimuli were presented on an SVGA monitor (with a frame rate of 60 Hz, noninterlaced), placed 70 cm from the participants and controlled by a 33-MHz 486-DX2 microcomputer. The background was black. A small circle 28′ in diameter was placed at the center of the screen as a fixation point. The color of the point served to identify the set of dots affected by the first probe.

The stimuli consisted of two spatially interspersed sets of dots, each set submitted to rigid motion independently of the other (see Figure 1). This motion was perceived as two semitransparent surfaces moving in the same area of visual space. The sets consisted of 100 dots each. One set was colored red and the other green. Red was created with the G and B guns of the CRT turned off and the R gun placed at its maximum level. Heterochromatic flicker photometry was then used, for each participant, to obtain a green (adjusting the G gun, with the R and B guns off) that was equiluminant with red.

All dots were 1 pixel in size (about 4.6′ wide and high). Dots were painted in randomly selected locations within an imaginary circle with a diameter of about 6.9° and centered on the fixation point. The average dot density within each set was about $2.7/\mathrm{deg}^2$. The different types of apparent motion used in the experiments

Table 1
Characteristics of the Participants by Experiment

Experiment	Age range	Sex		Handedness		% Rejected[a]
		Female	Male	Right	Left	
1	21–35	4	6	9	1	9
2	21–30	3	4	6	1	36
3	21–35	4	8	11	1	20
4	21–28	3	5	7	1	0

[a] Percentage of candidates rejected after initial screening on the task.

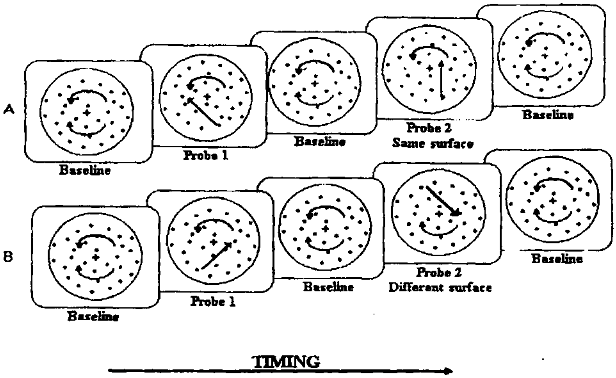

Figure 1. Sequence of events in all experiments. The background was actually black, and dots were either red or an isoluminant green (represented as black or gray). A: Events in same-surface trials. B: Events in different-surface trials. Probe motions affected only one surface at a time. Only the baseline in which the two sets of dots rotated in opposite directions is exhibited. Note that the probes were equivalent in the range of possible directions of motion for both types of trial.

were achieved by continuous redefinition of the position of the dots in synchrony with the video signal.

Two types of motion were used. The first type was rigid rotation around the fixation point. The speed of rotation was about 50 deg/s; this was defined as the baseline condition and was used to induce an organization of the perceptual field. In most situations the red dots rotated in a clockwise direction, and at the same time the green dots rotated in a counterclockwise direction. This baseline was perceived as two semitransparent surfaces moving in the same area of visual space. It was very difficult to pursue the rotating dots visually during the baseline.

Linear displacements were used as probe events (discriminanda) in a direction-judgment task that interrupted the rotatory baseline motion of only one surface (dots of one color) at a time. These brief shifts in motion direction occurred in the cardinal and diagonal directions at a speed of about 3 deg/s. Thus the possible directions varied in steps of 45°, resulting in eight alternatives. The displacements were partially coherent, with 60 dots moving in a common direction and the other 40 dots in randomly selected directions different from that of the coherent subset. This pattern of motion corresponds to what Scase, Braddick, and Raymond (1996) called a motion signal defined by the *same rule* in the presence of *random direction* noise. Partially coherent motion was used to compel attention to the complete ensemble, and the participants were warned that direction judgments based on individual dots could be misleading. In all experiments if a dot passed the border of the imaginary circle, it was wrapped around to an opposite but symmetrical position.

Trial structure and experimental design. On each trial, the color of the fixation point cued which surface was to be the first to move. Each trial began with a 700-ms baseline period in which the two sets of dots rotated in opposite directions (see Figure 1). Then a probe lasting 150 ms affected the surface that had been cued by the color of the fixation point for that trial. During the probe, the other surface continued to rotate. After this, both surfaces rotated in the baseline pattern for different intervals. Then a second 150-ms probe was presented. The directions of the two probes were always different. The resulting stimulus (probe) onset asynchronies (SOAs) took one of the following values: 300, 450, 600, 950, and 1200 ms.

In half of the trials, the second probe affected the same (cued) surface as the first probe (same-surface trials; see Figure 1A). In the other half of the trials, the second probe affected the other (uncued) surface (different-surface trials; Figure 1B). Thus, there were four possible combinations of probes, two for the same-surface trials (red–red, green–green) and two for the different-surface trials (red–green, green–red). The four possible combinations of probes were presented in equal proportions. At each SOA value, 80 trials each were presented for the same- and different-surface conditions, for a total of 800 trials in the session. The surface that was cued on each trial was selected randomly.

Procedure. The experiment took place in a room with dim illumination and was carried out in one session after about 20 warm-up trials. Participants sat in a comfortable chair with a headrest. Each trial began with stationary dots, and after fixating the center circle, the participants initiated stimulus motion by pressing the space bar of the computer keyboard. Fixation at the center was required until stimulus motion offset.

Participants were asked to report the direction of dominant (coherent) motion of the two probes in each trial. Responses were indicated on the arrow keys (and intermediate keys: *Home, PageUp, PageDown,* and *End*) of the numerical pad of the computer keyboard. After the offset of the stimulus motion, a message written above the dots asked for the first probe-judgment report by indicating the relevant set of dots (i.e., "Respond red").

After the response, another message asked for the second probe-judgment report. Accuracy was emphasized over response speed. Incorrect responses were signaled by a 500-ms beep on the computer loudspeaker.

Analysis. A separate repeated measures analysis of variance (ANOVA) was performed on the percentage correct scores across participants for the responses to the first probe and for the responses to the second probe. Because the color of the dots did not produce any significant effect in subsequent analysis, data were also collapsed over this factor (in this and all subsequent experiments). The main effects used were SOA (5 values) and surface (same-surface vs. different-surface trials). The Greenhouse–Geisser procedure was used to mitigate violations of the sphericity assumption in the repeated measures design, and the corresponding epsilon values are reported when appropriate (Jennings & Wood, 1976).

Results and Discussion

As can be seen in Figure 2, responses to the first probe were highly accurate (about 90%) for all values of SOA and surface, with no reliable differences as a function of these factors. In contrast, the percentage correct for the second probe was lower for different-surface trials than for same-surface trials, $F(1, 9) = 26.4, p < .0006$. The effect of SOA was also significant for this measure, $F(4, 36) = 13.5, p < .0001, \epsilon = .65$.

Examination of Figure 2 shows that there was a decreased accuracy for the second probes in different-surface trials, especially for the shorter SOA values. This is reflected in a significant SOA × Surface interaction, $F(4, 36) = 12.5, p < .0001, \epsilon = .66$. Planned comparisons indicate that accuracy for second probe responses did not differ reliably as a function of SOA for same-surface trials, whereas a highly significant effect of SOA was obtained in different-surface trials, $F(4, 36) = 16.9, p < .0001, \epsilon = .61$.

The time course of the interference was examined by planned comparisons between percentage correct in same- and different-surface trials for each value of the SOA between first and second probes. The interference is mitigated as SOA increases. Significantly lower accuracy was found for different-surface trials relative to same-surface trials for 300, 400, and 600 ms, $30.0 > F(1, 9) > 7.4$, and $.0001 < p < .024$. Accuracy did not differ for the two types of trial for SOAs of 950 and 1200 ms. At the shortest SOA (300 ms) the drop in performance for different-surface trials, compared with same-surface trials, was about 42%.

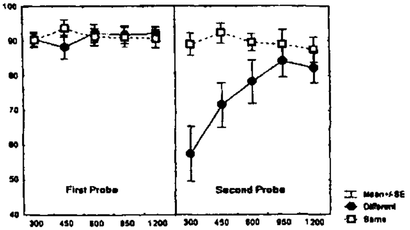

Figure 2. Percentage correct (±*SE*) as a function of stimulus onset asynchronies (in milliseconds) and type of trial in Experiment 1.

Judgments of motion-direction change were performed efficiently for the first probes in all trials. The surface affected by this probe was forewarned with 100% cue validity. In a formal sense, the paradigm here is analogous to the spatial cuing tasks (e.g., C. W. Eriksen & Yeh, 1985; Posner, 1980). The color cue for the first probe can be likened to the symbolic cues used in some situations to "push" attention to a location. Therefore, processing the first probes can be considered to have benefited from the possibility of concentrating attention on the appropriate surface.

In the case in which both events concerned the same surface, performance was just as accurate for second probes as for first probes at all SOA values. This result extends the finding of previous studies (Baylis & Driver, 1993; Duncan, 1984, 1993a, 1993b; Kramer et al., 1997; Valdes-Sosa, Cobo, & Pinilla, 1998; Vecera & Farah, 1994) that two attributes of the same object could be processed just as efficiently as one. Here two events affecting the same surface (or object file) are processed together without interference, even when they are very close in time.

The act of discriminating the first probe can be conceived as directing attention toward one surface in a manner comparable with peripheral (stimulus driven) cues that "pull" attention automatically to a location in spatial cuing tasks (for a review, see Yantis, 1996). However, it is important to note that in this experiment valid cues for the second probe (same surfaces as the first) were presented on 50% of the trials, in contrast to most spatial cuing tasks, where valid cues are usually much more frequent than invalid cues (see Theeuwes, 1993). It is perhaps more similar to the first target discrimination in the paradigm developed by LaBerge and collaborators (discussed above).

The most notable result was the large decrease in accuracy for reports about second probes when they affected a different surface than the first probe and for short delays between the probes. The duration of the interference on processing of the second probe in different-surface trials was slightly more than half a second, which is in close agreement with estimates of attentional dwell time (Ward et al., 1996) and duration of the *attentional blink* (Shapiro et al., 1994) induced by symbol processing.

This finding is consistent with a previous study in which a similar task was used except that only different-surface trials were presented and therefore the participants were encouraged to shift attention from one surface to another on every trial (Cobo, Pinilla, & Valdes-Sosa, 1999). In that study a somewhat smaller estimate of the dwell time (about 450 ms) was obtained. Comparison of the two studies suggests that most of the dwell time is not under strategic control. This result strengthens the conclusion that there is a limit to the number of different objects that can be attended to within short periods of time, and it extends measurements of attentional dwell time to brief events affecting relatively long-lasting object files.

Experiment 2: The Role of Separation Within the Same Plane

The previous experiment showed that processing interference is produced when attention is demanded by events presented in rapid succession first to one surface (defined by transparent motion) and then to another. In this and subsequent experiments the paradigm of Experiment 1 was modified so that the same interprobe SOA was used in all trials. The value selected (450 ms) was short enough to elicit interference between probes on different surfaces.

Because the two surfaces overlapped the same region of visual space in Experiment 1, this result is inconsistent with traditional space-based models in which all information arising within a compact and unitary locus is treated in a similar fashion. Here we further explore the role of spatial factors by varying the distance (in the projection plane) between the two sets of dots. In other words, division of attention was compared for superimposed and separate surfaces. Increased two-surface costs with separation should be expected with several, but not all, models of spatial attention (see Kramer et al., 1997). Controls for possible effects of eye movements were also included.

Method

Procedures were identical to those used in Experiment 1 except as follows. First, the SOA between probes was fixed at 450 ms. Second, the participants were required to participate in two sessions. In one session the red and green dots were superimposed within the same region of space as in the previous experiment. In the other session the red dots were plotted to the left of the fixation point, and the green dots to the right of the fixation point. In this case the two sets of dots were plotted within imaginary circles, the centers of which were separated about 5° from fixation. The order of the sessions was counterbalanced over participants. In each session 48 repetitions of same-surface trials and 48 repetitions of different-surface trials were presented, for a total of 192 trials across the two sessions.

The percentages of correct responses to the first and second probes were obtained for each type of trial for all participants. The percentage correct scores were submitted to a repeated measures ANOVA with separation (superimposed vs. separate surfaces), probe sequential order (first vs. second), and number of surfaces (same surface vs. different surface) as main effects.

Three of the participants were asked to participate in an additional session in which the horizontal electro-oculogram (EOG) was recorded with disk electrodes (Ag/AgCl) fixed with electrolytic paste just lateral to the external canthi. Interelectrode impedance was always kept below 5 kΩ. Bipolar derivations were used to record the EOG. The signals were filtered between 0.05–70 Hz (3 dB down). In addition, a notch filter with peak at the power line frequency was used. For calibration purposes the amplitude of the EOG was measured at the beginning and end of the session, for saccades directed from fixation toward targets displaced 1°, 3°, and 9° to the left and right. The average of about 12 measurements was used to estimate the voltage corresponding to a 1° eye movement.

The task with the superimposed condition was then repeated and the EOG recorded for the complete duration of each trial. All trials with deflections of the EOG exceeding the amplitude corresponding to a 1° saccade (about 8, 11, and 20 μvolts, respectively, for the different individuals) were purged from the analysis (36%, 66%, and 18% of the trials, respectively). Percentages correct for each type of trial were then estimated.

Results and Discussion

Accuracy in the direction-judgment task is shown in Figure 3. Overall accuracy was lower for superimposed surfaces (79%) than for separate surfaces (84%), $F(1, 6) = 15.18$, $p < .008$, and also lower when the two probes involved different surfaces (75%) rather than one surface (89%), $F(1, 6) = 35.0$, $p < .001$. The second discrimination was less accurate (78%) than the first (86%), $F(1, 6) = 36.5$, $p < .0009$.

Discriminations for the first probe were very accurate and very similar for all conditions in both sessions (about 89%). No effects of separation, or of number of surfaces, were found in the ANOVAs for these first probes. The drop in accuracy from the first to the second discrimination was only about 5% when the probes were on the same surface (not significant), and did not differ between the superimposed and separate-surface conditions. However, a large drop in accuracy from the first to the second judgment of about 24% was present when the probes concerned different surfaces, $F(1, 6) = 31.8$, $p < .0013$. This pattern was reflected in a significant interaction between probe order and number of surfaces, $F(1, 6) = 24.1$, $p < .003$.

The drop in accuracy from the first to the second probe was larger when the surfaces were superimposed (about 33%) than when they were separate (about 15%), a fact reflected by a significant interaction between separation and probe order, $F(1, 6) = 24.8$, $p < .0025$. This interaction arises because no difference in performance for first probes was found as a function of separation, whereas this factor had a significant effect on the second probes, $F(1, 6) = 20.7$, $p < .004$. Moreover, the interaction between separation and number of surfaces was significant, $F(1, 6) = 31.8$, $p <$

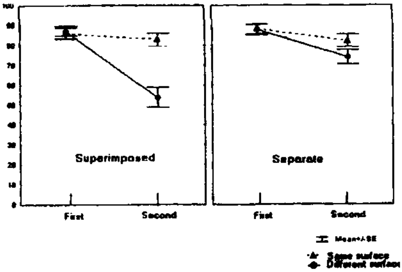

Figure 3. Percentage correct ($\pm SE$) as a function of separation, type of trial, and probe sequential order in Experiment 2.

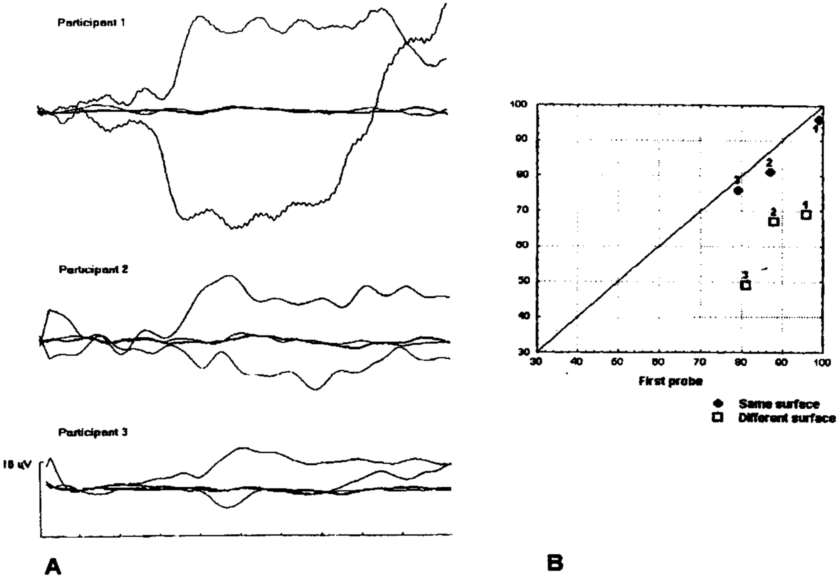

Figure 4. Panel A shows the average horizontal electro-oculograms (EOGs) for 3 individuals. The traces with large deflections correspond to calibration measurements in which saccades were made from fixation toward targets placed 1° to the left (positive) or right (negative) and are the average of about 10 measurements. The nearly flat lines represent average EOG recordings related to the trials that remained after purging those with excessive eye movements. The thin lines represent traces related to same-surface trials, and the thick lines represent traces related to different-surface trials, in the subsequent experimental session. The recording begins about 100 ms before the first probe and ends about 250 ms after the second probe offset. Each time tick corresponds to 100 ms. Panel B shows the percentage correct for the 3 individuals (labeled with numbers) in the control for eye movements from Experiment 2 as a function of type of trial and probe sequential order. The superimposed condition was used. Percentage correct was calculated for trials on which eye movements were less than 1° of arc. Note that the results are plotted differently than in other figures, with percentage correct for the first probe on the *x*-axis and percentage correct for the second probe on the *y*-axis. Equal performance for the first and second probes is represented by the principal diagonal. In all individuals, responses from same-surface trials were close to the diagonal, whereas responses from different-surface trials were in the lower right quadrant, indicating a two-surface performance decrement.

.0013, with no effects on accuracy when the two probes concerned the same surface, whereas performance was better for separate than for superimposed surfaces when the two probes affected different surfaces, $F(1, 6) = 20.8$, $p < .004$. The triple interaction between separation, probe order, and number of surfaces was also significant, $F(1, 6) = 13.2$, $p < .01$.

As shown in Figure 4B, the pattern of results described above for the separate condition was present in each of the individuals for which the EOG was recorded to eliminate trials with eye movements larger than 1° (note that the diameter of the stimulus aperture was about 7°). All the individuals produced accurate and practically equivalent responses for the two probes in the same-surface condition.

They also presented substantial decrements in accuracy for the second probe compared with the first in different-surface trials. The average EOG recordings (see Figure 4A) show that no systematic difference was present for the residual eye movements between the two types of trial, and they serve as a check on the effectiveness of the eye movement rejection criterion.[2]

In summary, all discriminations on the first probes were accurate. Only a small amount of interference was found for judgments on second probes if they concerned the same surface as the first probe, and this effect was equivalent for superimposed and separate surfaces. In contrast, a large disadvantage was found for discriminations connected with second probes if the probes affected different surfaces. This interference was about twice as large for superimposed surfaces as for separate surfaces. Elimination of trials with eye movements larger than 1° did not modify the results for the superimposed surface condition.

First, the contribution of lower order sensory factors must be discussed. In particular, retinal eccentricity differed in the separate and superimposed conditions of the present experiment, and, for example, increased retinal eccentricity enhances metacontrast masking (Breitmeyer, 1984). This could affect the two-object disadvantage in some situations (Kramer et al., 1997). However, lower order sensory factors, if present, should have affected the motion signals equivalently in same- and different-surface trials. Therefore, changes in eccentricity due to these factors would have affected both types of trial, yet separation only influenced the second response in the latter type of trial. Therefore, separation seems to have specifically affected the switching of attention from one surface to another.

Next, the role of eye movements for the superimposed condition is considered. When effectiveness of fixation was controlled for the superimposed condition (by eliminating trials with gaze deviations larger than 1°), the same pattern of performance was obtained as in the session without eye movement control. Also, the residual EOG was equivalent in both types of trial, indicating that they were not associated with differential patterns of gaze direction. These results were to be expected for several reasons. First, rotational eye movements are hard to follow, and these preceded and followed each probe. Second, the participant could not predict which surface was to be affected by the critical second probe in any trial, and the probes were too brief (about 150 ms) for their perception to be affected by reflex eye movements. And last, but most important, any change in fixation would have affected in exactly the same way the attended and the unattended surface because these were completely superimposed.

Finally, the lack of increased two-surface costs as a consequence of surface separation allows us to select between pairs of models in different classes. Among serial attentional models, those with a slowly shifting focus of attention are falsified, albeit those with discrete, very fast, spatial attentional shifts are not (Kramer et al., 1997). Among parallel processing models, those that have limits on the area over which attention can be distributed would predict smaller costs in the superimposed condition and are thus rejected. Only unlimited-capacity parallel models wou be consistent with the data. This experiment therefc restricts the set of possible mechanisms involved.

However, more important than the lack of increased co with separation is that the opposite effect was found: It w easier to shift attention from one to another for separate th for superimposed surfaces. This reveals a spatial requi ment that is different from the role traditionally assigned space in attention. Here we find that surface proximi (created by transparent motion) can hamper the division attention, and this is a novel finding. None of the previous mentioned space-based models can explain this resu Moreover, simple object-based models are also in troub The findings cannot be explained by a general limitation dividing attention between two objects (there are tv surfaces in both the superimposed and separate condition An additional process must be involved. The superimpo tion of two sources of motion signals within the same regi of space possibly generates the need for "noise reduction or ambiguity resolution. This point is expanded in t General Discussion section.

Experiment 3: The Role of Spatial-Frequency Content, Color, and Relative Motion

The first goal of this experiment was to follow up t suggestion that differences in spatial-frequency conte permit the selection of features from one of several superi posed objects (Watt, 1988). Thus a low-level filter wou make selection of objects (as higher level entities) unnece sary. Although the images generated by the two sets of dc used in the previous experiments probably did not diff systematically in spatial-frequency content, a more str control for this possibility was introduced in this experime

Here, the initial placement of one set of dots was a mirr image of the placement of the other, obtained by rotati around the fixation point. Moreover, the probe motio consisted of two phases, the second a reverse motion of t first, returning each dot to the position occupied at t beginning of the probe. These restrictions on the positioni of the dots ensured that the spatial-frequency content of t images corresponding to the two ensembles was identi and did not vary within each trial.

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[2] An additional control for the effects of eye movements in separate surface condition was conducted with a new group o participants. In this condition, a tendency toward looking direc at the probes must be suppressed. Participants were instructed one block to maintain fixation on the center, as in the m experiment. In the other block they were asked to make a sacc toward the cued surface where the first probe was to be present The mean drop in accuracy of the second probe with respect to first probe in the two-surface condition with central fixation about 8%. With saccades toward the first probes, this drop about 19%, a difference that was significant ($p < .05$). Looking the first probe places the second probe farther in the vis periphery in different-surface trials; therefore, this effect expected. The high accuracy for second probes in the differe surface trials in the main experiment suggests that participa were effectively maintaining fixation.

The second goal of the experiment was to examine the role of relative motion with more care. According to object-based models, the attentional costs described in previous experiments are strictly dependent on the segmentation of the visual scene. As mentioned before, in these models attention is directed toward preattentively defined perceptual objects, created either by the gestalt principles of scene organization or related early processes (Palmer & Rock, 1994). Therefore, a weak segmentation of the image into different perceptual groups should hamper the selective allocation of attention.

Two conditions were compared to test this prediction. In the first condition, two sets of dots rotated in opposite directions during the baseline, inducing a percept of two objects (as in the previous experiments). In the second condition, in which all dots rotated in the same direction during the baseline, the percept of only one rotating object was induced. It was expected that the two-surface disadvantage would be attenuated in the one-object condition. This last condition also permitted the contribution of color to the division of attention to be assessed by itself. Because the dots in the different surfaces were of distinct colors, the effects of previous experiments could be due to attentional selection based on this attribute. Color has been shown to be very effective in guiding attention (Treisman, 1988).

Method

The stimuli and procedure in this experiment were identical to those used in the superimposed condition of Experiment 2, except as follows. At the beginning of each trial, and before the rotational baseline, the set of red dots was randomly repositioned. Then the green dots were placed at mirror positions with respect to the red dots, in other words with a 180° phase difference around the fixation point. This was done to ensure identical spatial-frequency composition of the images generated by the two sets of dots. This initial rotation and subsequent baseline rotations did not affect the frequency content of the image corresponding to each set of dots. Note that the Fourier transforms of two mirror images (180° mirror rotation) will be conjugates of each other. The two conjugates will have the same module (but a different phase structure). Therefore, the corresponding spatial-frequency spectra will be the same.

In addition, the first probe motion was broken down into two steps, one lasting 75 ms followed by another of the same duration but with each dot moving in reverse direction as in the first phase. This returned the dots to the same spatial configuration existing at the beginning of the probe. This maneuver was carried out to maintain the image spatial-frequency composition corresponding to each set of dots invariant within a trial. The second probe was produced as in previous experiments.

Moreover, two different patterns of rotational baseline motion were used. Either the two sets of dots rotated in opposite directions as in previous experiments, or both sets of dots rotated in the same (clockwise) direction. This induced the percept of only one bicolor rotating object. Each participant was presented with two blocks of trials, one in which a one-object baseline was used, and the other in which the two-object baseline was used. The order of the blocks was counterbalanced over participants. In each block 80 repetitions of same-surface trials and 80 repetitions of different-surface trials were presented.

The percentage correct scores were submitted to a repeated measures ANOVA with number of objects (in the baseline), probe sequential order (first vs. second), and set repetition (same set vs. different set) as main effects, and additional ANOVAs with the last two factors were also performed for the data from each block separately. In the block with two objects in the baseline, set repetition corresponded to the factor number of surfaces used in the previous experiment.

Results and Discussion

The mean accuracy in the direction-judgment task is shown as a function of the number of objects in the baseline in Figure 5. For the block in which two objects were present in the baseline, the results are very similar to the corresponding conditions of Experiments 2 and 4 (see below). Reports for the first probe were very accurate for both the same-set and different-set conditions (about 74% correct). There was a small (nonsignificant) increase in the accuracy of the second as compared with the first discrimination for the same-set condition (about 6%). The second discrimination was about 34% less accurate than the first when the two probes concerned different sets of dots (different surfaces).

These results were reflected in the repeated measures ANOVA for this block by highly significant effects of both probe sequential order, $F(1, 7) = 29.1$, $p < .001$, and set repetition, $F(1, 7) = 20.4$, $p < .003$, as well as the interaction between the two factors, $F(1, 7) = 85.6$, $p < .0001$. The interaction reflects the fact that whereas there was no difference in accuracy for the first discrimination as a function of the set repetition, the judgment corresponding to the second probe was less accurate for the different-set condition compared with the same-set condition, $F(1, 7) = 58.3$, $p < .0001$ (see Figure 5).

A very different pattern of results was obtained in the one-object block (see Figure 5). In this block, a small (nonsignificant) increase in accuracy of about 7% for the second probe in relation to the first probe was observed when both affected the same set of dots. A small (also nonsignificant) decrease in accuracy of 9% was seen for the

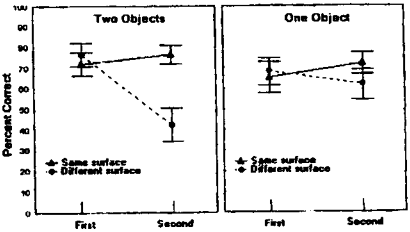

Figure 5. Percentage correct ($\pm SE$) as a function of motion phase, distribution of attention, and probe sequential order in Experiment 3. The panel on the left corresponds to the two-object baseline (the two sets of dots rotated in opposite directions). The panel on the right corresponds to the one-object baseline (both sets of dots rotated in the same direction).

same comparison when the two probes involved different sets of dots. In the repeated measures ANOVA for this block, probe sequential order was not significant, whereas set repetition, $F(1, 7) = 28.4$, $p < .001$, and the interaction of the two factors, $F(1, 7) = 6.5$, $p < .04$, were significant. This interaction was due to the fact that whereas first-probe scores were equivalent, there was a small but significant difference for the second-probe scores, $F(1, 7) = 13.1$, $p < .009$, as a function of set repetition (see Figure 5).

The different pattern of results as a function of the number of objects in the baseline was reflected in a significant three-way interaction, $F(1, 7) = 61.0$, $p < .0001$, in the repeated measures ANOVA with all the data. Planned comparisons showed that the interaction of probe sequential order and set repetition was significant, $F(1, 7) = 6.5$, $p < .04$, only if the dots rotated in opposite directions. This means that when attention switches from dots of one color to dots of another color, interference is large only when the two sets are parsed into separate objects by relative motion.

On the one hand, we conclude that the attentional effects of the previous experiments were replicated despite careful controls that kept the spatial-frequency content of the two surfaces equivalent. This rules out the possibility that selective attention to one set of dots was reached by differential processing of spatial-frequency channels as suggested by Watt (1988). On the other hand, the two-set disadvantage of previous experiments was severely attenuated when both sets of dots moved in the same direction. This indicates that color by itself imposes weak constraints on the division of attention if common fate unites all the dots into one surface or object. The existence of divided-attention costs when the two sets of dots are parsed into different surfaces by relative motion is consistent with object-based attentional selection.

Experiment 4: The Role of Separation in Depth and of Color

It has been previously suggested that superimposed objects are perceived at different depth planes (see Duncan, 1984; Lavie & Driver, 1996) and that apparent object-based constraints are really due to three-dimensional spatial constraints on the distribution of attention. Several reviewers pointed out that this alternative might explain any difficulty in dividing attention between surfaces defined by transparent motion, which could be construed as one object placed on top of the other. Constraints due to distance in depth would therefore explain the two-surface disadvantage.

This argument is plausible given previous work that has either demonstrated performance costs with shifts of attention in depth or has evinced effects of depth separation on the speed of visual search. This has been found with real-world objects (Downing & Pinker, 1985; Gawryszewski, Riggio, Rizzolatti, & Umiltà, 1987) as well as with planes defined by stereograms (Andersen, 1990; Andersen & Kramer, 1993; Nakayama & Silverman, 1986). The argument requires that the two surfaces be registered at different depth planes in an internal three-dimensional representation of visual space.

The purpose of the present experiment was to examine this alternative explanation by explicitly manipulating the perceived depth of the two sets of dots (by means of the binocular disparity of the component dots). If the difficulty in shifting attention between two surfaces defined by transparent motion is merely a consequence of having to move from one depth plane to another, then similar costs should arise even if the two sets of dots are stationary but separated in subjective depth. Furthermore, adding binocular disparity cues to relative motion should increase subjective distance between these planes, leading to increased costs for divided attention.

In addition, the influence of color on the distribution of attention was again examined. One of the conditions consisted of red and green dots that were spatially interspersed as in the previous experiments but were stationary during the baseline period. Discrimination accuracy was compared for pairs of probes with the same color and with different colors.

Finally, the effect of similarity in direction between the two probes on the accuracy of second-probe judgments was examined. This was motivated by reports of a large influence of between-targets similarity in the attentional blink phenomenon (Shapiro et al., 1994; Ward et al., 1997).

Method

The stimuli and procedure in this experiment were identical to those of the superimposed condition of Experiment 2 except as follows. Four different blocks of trials were used. In the zero-disparity/rotatory-baseline block, the two sets of dots were presented at the same depth as the fixation point and were segregated by having each set rotate in a different direction during the baseline (as in Experiments 1 and 2). In the zero-disparity/stationary-baseline block, stimuli consisted of dots at rest during the baseline that were always at the same depth as the fixation point. In the disparity/stationary-baseline block, the two sets of dots were at rest during the baseline, but the green dots were presented with crossed disparities, whereas the red dots were presented with uncrossed disparities, and thus perceived at different depth planes straddling the fixation point. In the disparity/rotatory-baseline block, the two surfaces were segregated by relative motion and also by different subjective depths.

Binocular disparity was generated by placing a Keystone stereoscope in a hood covering the computer monitor screen and presenting different modifications of the stimulus display to each eye. The eye-to-screen distance was reduced to 23 cm. This increased the radius of the imaginary circle within which the dots were plotted to about 20°. The fixation dot was presented with zero binocular disparity. The red dots were shifted by 5 pixels to the left, whereas the green dots were shifted 5 pixels to the right, for the image presented to the right eye. This shift corresponded to an angular disparity of 31.5′. The image presented to the left eye was not modified. The virtual planes thus created were separated about 1.5 cm from the fixation plane, or the equivalent of 3.73° of visual angle. All the participants rated the virtual separation between planes (about 3 cm) as much larger than that induced by relative motion, which was considered to correspond to a few millimeters' separation.

To evaluate the perceptual grouping elicited by these displays, a group of nine judges (none of whom participated in the experiment) was shown for 5 s each type of baseline in a random order. The judges rated each stimulus on a 5-point scale ranging from 1 (*differently colored dots belong to the same object*) to 5 (*differently colored dots belong to two completely different objects*). They were also asked to rate the subjective separation in depth of the surfaces perceived in the zero-disparity/moving-baseline and the disparity/static-baseline conditions on a 10-point scale. The judges were shown a 3-cm separation on a ruler, which was assigned a rating of 10, whereas no separation at all was to be considered zero.

Participants in the experiment were first screened for stereovision sensitivity. This was done by asking them to report the relative subjective depth with respect to the fixation point of the same stimuli used in the experiment. Several screening trials were presented in which the type of disparity (crossed or uncrossed) corresponding to each surface was randomly switched (in other words, the red dots should have been perceived in front of the green in some trials and behind them in the others). Ten such trials were presented, which all the participants reported with perfect accuracy.

In each block 60 repetitions of same-surface trials and 60 repetitions of different-surface trials were presented. Two blocks were presented in each of two sessions. The order in which the blocks were presented was counterbalanced over participants. The use of these four blocks allows for a factorial manipulation of disparity and motion.

The percentage correct scores from the four blocks for all the participants were submitted to separate repeated measures ANOVAs for the stationary and rotatory baselines, with three main effects, depth separation (same depth vs. different depth), probe sequential order (first vs. second), and set repetition (same vs. different set of dots). Note that for the rotating dots, set repetition was equivalent to the surface factor of previous experiments.

Results and Discussion

The judges perceived the zero-disparity/static-baseline condition as containing only one object (median rating of 2), whereas the zero-disparity/moving-baseline, the disparity/static-baseline, and the disparity/moving baseline conditions were perceived as containing two different objects (median ratings of 4, 4, and 5, respectively). The ratings of independence from the zero-disparity/static-baseline condition were significantly different ($p < .02$) from all those from the conditions with moving baselines in paired Student's t and Wilcoxon tests. The difference in ratings of independence from the disparity/static-baseline and the zero-disparity/static-baseline just missed significance ($p < .1$). The judges (as well as the participants after debriefing) perceived the separation between surfaces generated by binocular disparity to be larger than the separation induced by relative motion. The median rating of separation for the disparity/static-baseline was 8 and for the zero-disparity/moving-baseline was 2. This difference was significant in paired t and Wilcoxon tests ($p < .01$).

Mean accuracy in the task for all conditions is depicted in Figure 6. The most important results are that the distance in depth between the two sets of dots produced no effect on accuracy as is apparent in Figure 6. The plots of data from same-depth and different-depth blocks are practically identical for corresponding conditions. This was confirmed by nonsignificant outcomes in the repeated measures ANOVAs related to depth separation, as well as the lack of any significant interaction with any other variable. In other words, separating the two groups of dots did not make shifting attention from one to another more difficult, for either stationary or rotatory baselines.

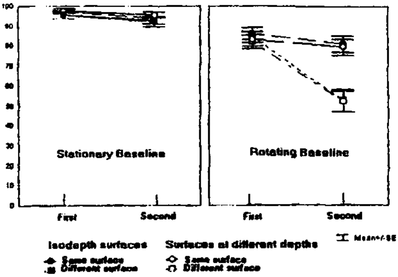

Figure 6. Percentage correct (±*SE*) in Experiment 4 as a function of baseline definition, type of trial, and probe sequential order. The panel on the left corresponds to the stationary baseline in which one object was perceived. The panel on the right corresponds to the two-object baseline (both sets of dots rotated in opposite directions).

However, the nature of the baseline had striking effects on performance. The discrimination of probe direction was more accurate for the stationary baselines than for the rotatory baseline, $F(1, 11) = 63.9$, $p < .00001$, with overall percentage correct scores of 95% and 76%, respectively. Moreover, discriminations were equally good for both probes with the stationary baseline, which was reflected in uniformly nonsignificant effects in the separate repeated measures ANOVA for these data.

In contrast with the stationary baselines, the pattern for rotatory baselines was very similar to that found in previous experiments. The responses to second probes were less accurate than responses to the first probe (67% vs. 85%), $F(1, 11) = 46.6$, $p < .00001$, and accuracy was lower when the two discriminations involved different surfaces (68%) than when they concerned the same surface (83%), $F(1, 11) = 55.9$, $p < .00001$. Also, the interaction between probe order and set repetition was highly significant, $F(1, 11) = 35.5$, $p < .00002$. This interaction was due to the equivalent accuracy of first-probe responses for the two set repetition levels, whereas the same contrast was highly significant for second probes, $F(1, 11) = 49.1$, $p < .00002$. Discrimination of second probe direction was 29% less accurate if it concerned a different set, rather than the same set, of dots.

To examine the role of similarity between the first and second probe directions, data from the zero-disparity/motion baseline condition were used. This set of data was chosen because it was equivalent to similar conditions in all other experiments and because it involved the largest group of participants (and thus the largest statistical power) in the whole series of experiments. A repeated measures ANOVA was performed on the accuracy of second-probe judgments with the difference in visual angle (measured as the smallest angle) between probes as the main effect, with four levels (45°, 90°, 135°, and 180°).

The between-probes difference in visual angle had a significant effect on second-probe accuracy, $F(3, 33) = 4.4$, $p < .022$, $\epsilon = .83$. The lowest accuracy was related to the 45° and 180° differences in angle (adjacent and opposite directions), and the highest accuracy was for 90° and 135°. A quadratic contrast was found to be significant. However, the difference in angle did not interact with surface, $F(3, 33) < 1$. Thus similarity between the two probes had a significant effect on judgments of the second probe that was independent of the type of trial. This result is taken up again in the General Discussion section.

Several conclusions are suggested by this experiment. First, no interference was found when attention switched between differently colored stationary dots that were interspersed on the same depth plane, a stimulus configuration that is readily perceived as a unitary bicolored object. This finding stands in stark contrast to the situation in which the two sets of dots rotate in opposite directions, and it confirms the conclusions derived from Experiment 3. Therefore, neither color by itself nor the conjunction of color with the probe motion was sufficient to elicit the effects described in previous experiments. Of course, color possibly could have contributed to surface segmentation in these experiments, but by itself it was not a sufficiently powerful cue to influence the division of attention. Dots of one color interspersed with those of another possibly lack the "uniform connectedness" associated with distinct objects (Palmer & Rock, 1994).

Second, the two-surface cost was absent if the surfaces were segregated only by depth (the dots were stationary during the baseline). This result was obtained despite the fact that the subjective depth separation produced by binocular disparity was clearly larger than the ambiguous illusion induced by relative motion. In fact, the displays without binocular disparity (as those in Experiments 1, 2, and 4) were seen as quite flat, with only a minimal distance in depth between the two surfaces. The presence of two-surface costs when there was relative motion and the absence of the costs in the disparity/stationary-baseline condition cannot be reconciled with an explanation based solely on proximity effects. These results are a strong rebuttal of the idea that the attentional costs described in previous experiments are merely due to spatial selection of depth planes within an internal mental representation.

In fact, there is another problem with this explanation. The depth illusion induced by transparent motion is ambiguous. The attended surface is seen as closer and the relative position of the surfaces is seen as changing when attention switches. This suggests that relative positions in three-dimensional space are a consequence of attentional selection and are not the basis for this selection.

This lack of depth-related costs apparently contradicts some reports (Andersen, 1990; Andersen & Kramer, 1993; Downing & Pinker, 1985; Nakayama & Silverman, 1986). However, it agrees with other reports that suggest that the spotlight is to some degree "depth-blind" (Ghirardelli & Folk, 1996; Iavecchia & Folk, 1995). The reasons for these disagreements are not completely clear because there are many methodological differences in the studies cited.

Recent work carried out by Nakayama and colleagues is consistent with our results. They found that during spatial cuing experiments using stereoscopic images, the spread of attention is partly obligatory across well-formed surfaces, even if the surfaces span a range of stereoscopic depths (He & Nakayama, 1995). Moreover, selectivity is impaired if the items are coplanar or rest on a common surface, despite differences in subjective depth. As in our studies, belonging to the same surface (a form of perceptual grouping) produced larger attentional benefits than proximity in three-dimensional space, whereas having to shift attention between surfaces was more costly than moving a larger distance along the same surface. The size of the shift in subjective space (within limits) may not be as important as belonging to two different perceptual groups.

However, the negative results of this experiment are also problematic for simple object-based explanations. The two stationary surfaces separated by depth were perceived clearly as different objects. If the limitation in dividing attention concerns only the number of different objects that can be processed at once, a two-surface cost should have been obtained with static surfaces generated by depth separation. Perhaps there is something special about moving surfaces. We return to this issue in the General Discussion section.

General Discussion

Summary of Findings

Four experiments were performed with transparent surfaces generated by two sets of dots that rotated in opposite directions. If two probes affected the same surface, then judging their direction was performed without interference for a wide range of between-probes SOAs (explored down to 300 ms). Likewise, if the probes affected different surfaces but the SOAs were larger than 600 ms, then no interference was found. In contrast, accuracy for a probe affecting a surface different from that affected by a previous probe was severely impaired for SOAs lower than 600 ms, and the effect was greater for shorter intervals. This two-surface decrement was a very robust effect, with reductions in accuracy compared with the one-surface condition of about 30% to 40%, for SOAs between 300 and 450 ms across all experiments. Furthermore, the observers reported that the misjudged events also escaped detection on many trials.

The two-surface cost was obtained even when the spatial-frequency content of the two surfaces was equated, but it was largely eliminated for baselines in which the two sets of dots were integrated into one object, either by having them rotate in the same direction or by having them stand still. The two-surface disadvantage was larger when the two sets of dots were superimposed than when they were separated into two different visual hemifields. The two-surface disadvantage was not elicited when a relatively large subjective separation in depth was induced by means of binocular disparity between two stationary surfaces (despite their being clearly perceived as different objects), nor did depth differences enhance the disadvantage for rotating dots.

Two-Surface Interference Does Not Depend on Perceptual or Response-Related Factors

The impairment in processing the second probe for the two-surface condition relative to the one-surface condition is not explained readily in terms of purely sensory or perceptual factors, because these were essentially equivalent in these two types of trials. For example, the amount of forward masking between motion signals (first probe masking the second) would have been the identical for same- and different-surface trials.

At first glance it would be plausible to conceive probes as competing for perceptual analyzers (Allport, 1971; Treisman, 1969), in what Duncan (1984) termed *discrimination-based* models of attention. However, this explanation is also readily dismissed because the same pair of discriminations performed accurately in the one-surface condition cannot be performed without interference in the two-surface condition (for short SOAs).

Several other processing loci for the interference must be considered (Palmer, 1995). The list includes short-term memory failures, limitations in making two decisions at the same time, and limitations at the response organization stage. The last two alternatives are particularly interesting given the finding by Fagot and Pashler (1992) that the psychological refractory period is also present for tasks requiring responses to two attributes of the same object.

However, these alternatives can also be eliminated from consideration because they also would have affected same- and different-surface trials to the same degree. The memory load and type and number of the decisions and responses, as well as the internal time structure of the two types of trial, were equivalent. All this points to an attentional explanation for the results.

Relationship to Previous Divided-Attention Studies

These results are in line with previous studies showing better performance in judging two attributes of one object than in judging two attributes distributed across different objects (Baylis & Driver, 1993; Duncan, 1984, 1993a, 1993b; Kramer et al., 1997; Lavie & Driver, 1996; Vecera, 1994; Vecera & Farah, 1994). For the specific case of motion, a two-object disadvantage has been obtained with discriminations concerning spatially separate kinematograms (Experiment 3 of Duncan & Nimmo-Smith, 1996) and for superimposed components of transparent motion (Valdes-Sosa, Cobo, & Pinilla, 1998). Together with the last study, the present findings extend the logic of Duncan to a situation in which possible confounds with spatial factors or lower order filtering are eliminated (see below).

However, the critical difference of the present and previous findings (including Valdes-Sosa, Cobo, & Pinilla, 1998) is that here the two-object decrement involved brief events that modified preexisting objects. In the earlier studies, permanent attributes lasting for the lifetime of the object were judged. The implications of this distinction are elaborated on below.

The other important difference from the previous studies is that the judged attributes were separated in time. Our results suggest that the processing of the first probe requires focusing attention on the cued surface and that there is a certain inertia before attention can be reassigned to the other surface. The long delays in reassigning attention between objects are consistent with recent studies of attentional dwell time (Duncan et al., 1994; Ward et al., 1996) and the attentional blink (Shapiro et al., 1994).

Similarity between the first target and the first distracter that follows it enhances the attentional blink (Shapiro et al., 1994; Ward et al., 1997). This factor is even more important in repetition blindness (Kanwisher, 1987). Although a significant effect of directional similarity between probes in a trial was found in Experiment 4, this effect was additive with the same- versus different-surface effect. Therefore the two-surface decrement is more similar to interference in attentional dwell time studies that use displays without distractors (e.g., Experiment 1, Ward et al., 1997).

A Different Role for Space

Traditional space-based models that postulate a compact attentional locus in two-dimensional space (*Cartesian* models, according to Nakayama & He, 1995) are clearly inconsistent with the findings presented in this article. On these models there should not be any difficulty in dividing attention between components of transparent motion (for a detailed discussion of this point, see Valdes-Sosa, Bobes, et al., 1998; Valdes-Sosa, Cobo, & Pinilla, 1998). An explanation based on extensions of traditional models to three-dimensional representations of visual space can also be discarded as discussed in Experiment 4. The two-surface cost is not merely a consequence of subjective separation in depth, because attention can be divided efficiently between stationary surfaces that differ substantially in subjective distance from the observer.

It could be argued that attention is guided by perceptual organization (or feature information) but still allocated to locations in space. This position is taken both by the *grouped-array account* (Kramer et al., 1997; Vecera, 1994; Vecera & Farah, 1994) and also by other modified spatial-selection theories such as guided search (Treisman, 1988; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989). This implies a non-Cartesian mechanism of attentional distribution and thus overcomes arguments directed against compact-locus models.

However, by postulating that attention is allocated to locations, these models are conceived as exhibiting the proximity and location-inertia effects mentioned in the introduction. Several studies have been conducted in an effort to support grouped arrays over higher order representations of objects by showing either proximity benefits or location inertia in visual displays (e.g., Luck, Fan, & Hillyard, 1993; Kramer et al., 1997). Our results are incompatible with these traditional spatial mechanisms. Dots from the uncued surface were generally near to dots from the cued surface, and despite this a two-surface cost was evinced. Substantial inertia was found in switching attention between surfaces. However, because dots from the uncued surface frequently occupied the same locations previously taken by dots from the attended surface, location inertia was improbable.

In fact, the results of Experiment 2 indicate that proximity of the surfaces hampered, instead of enhancing, the division of attention between the two objects. This is a different role than the one traditionally postulated for space. In earlier studies of divided attention, performance was improved by decreasing the distance between items (Downing & Pinker, 1985; Hoffman & Nelson, 1981; Hoffman, Nelson, & Houck, 1983; Laberge & Brown, 1989). In summary, any model that is based on the allocation of attention to locations will have serious difficulties in explaining our data, given the failure to uncover evidence for the hallmarks of spatial attention: proximity effects and temporal inertia of attention assigned to locations. While rejecting the traditional role for spatial mechanisms, the data indicate that interference between surfaces is increased by proximity. In addition to this apparently bizarre role for spatial factors, diffuse selection of regions of visual space may be a prerequisite for object-based selection as discussed by Lavie and Driver (1996).

Two-Surface Interference Is Not Due to Low-Level Feature Filtering

Attentional selection in our experiments could have been based on simple nonspatial attributes. More specifically, the two-surface decrement could arise if attending to probes on one surface would activate low-level sensory filters that would exclude probes generated on the other surface. Here we examine several possible types of filters.

Filters could be based on motion properties. Filters distinguishing moving and stationary items (McLeod et al., 1988; McLeod et al., 1991; O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997) or different directions or types of motion (Driver & McLeod, 1992; Watanabe et al., 1997) have been used to explain some attentional effects. However, in the present experiments, specific motion properties could not differentiate same- and different-surface probes. These two types of probes moved at exactly the same speeds and in exactly the same eight possible directions.

Another type of filter could be based on the spatial-frequency content of the two stimuli (Kramer & Jacobson, 1991; Watt, 1988). This alternative was also discarded. First, the spatial-frequency content was an unreliable clue for surface segregation, because the dot configurations were varied randomly from trial to trial. Second (and more important), the different-surface cost was obtained in Experiment 3, where the two sets of dots were carefully matched in the spatial-frequency composition.

The filters could be based on color. Several experiments indicate a powerful role for color in attention (Bundesen & Pedersen, 1983; Kramer & Jacobson, 1991; Treisman & Sato, 1990; Wolfe et al., 1989). Furthermore, Croner and Albright (1997) suggested that color can modulate directional motion filters. However, in two of our experiments when the relative motion of the two surfaces was eliminated (in the same-direction-of-rotation condition of Experiment 3 and in the stationary-baseline condition of Experiment 4), attention could be divided at little cost between dots of different colors. This finding indicates that neither color filtering by itself nor directional filters gated by color (conjunctions of direction and color) can explain the two-surface costs. This does not deny a contribution of color to the segregation of the two surfaces, but it does eliminate a color filter as a sufficient explanation of the data.

Interpretation of the Two-Surface Interference

Having eliminated classical spatial selection (that views proximity as favorable to sharing attention) and low-level sensory filtering, the most plausible explanation is that probes are selected according to which perceptual group or object file they affect. Thus the previous history of the visual scene during the baseline period determines how each probe is treated. This can be conceptualized as follows. During the baseline an object file is set up for each surface. One direction of rotation and one color are univocally associated with each set of dots during the baseline. This color, and the continued rotation of the surface not affected by a probe, probably served to preserve the segregation and identity of the two object files during probe motion. Probes are selected not by their physical (sensory) attributes but in terms of the object file to which they belong. This idea is in line with theories in which perceptual linkage leads to the acceptance or rejection of whole groups of elements (Duncan, 1995; Duncan & Humphreys, 1989, 1992; Nakayama et al., 1995).

However, the data do not provide an unspecific endorsement of object-based models. Two pieces of evidence indicate that the limitation in sharing attention is not wholly a general inability to process two objects at the same time. Two-surface interference was modest when the surfaces were not superimposed (Experiment 2). Practically no interference was present when two static surfaces were generated by stereopsis (Experiment 4). In both cases participants clearly perceived two different objects. These facts suggest that the conditions necessary for attentional interference include, in addition to the existence of distinct objects, close spatial proximity of motion signals that cannot be generated by the same source.

This possibility is related to the proposal that competition for receptive fields is the origin of the limited capacity demonstrated in divided-attention studies (Desimone & Duncan, 1995; Luck, Girelli, McDermott, & Ford, 1997). Suppression of irrelevant inputs would be necessary to reduce signal ambiguity from receptive fields (see the ambiguity resolution theory of Luck, Girelli, et al., 1997). In our paradigm conflicting nearby and conflicting motion signals would generate ambiguity and therefore the need for suppression, hence the larger interference in the superimposed (where ambiguity of motion signals would be maximal) as opposed to the separated surface condition of Experiment 2. The absence of motion ambiguity would also explain why no suppression was elicited between stationary surfaces separated in depth by disparity clues in Experiment

4. In other words, noise signals may play an important role in the two-surface decrement.

Empirical evidence in favor of these ideas can be found in several studies that have examined the effect of drawing attention away from an optimal stimulus placed within the receptive field of monkey extrastriate neurons. Suppression of V4 cell firing is larger when the competing item was placed within the same receptive field as compared with when it was placed outside (Chelazzi & Desimone, 1994; Chelazzi, Miller, Duncan, & Desimone, 1993; Luck, Chelazzi, Hillyard, & Desimone, 1997; Moran & Desimone, 1985). Perhaps of more relevance to our argument, Treue and Maunsell (1996) recently reported similar results for directionally sensitive motion cells from MT and MST. Attentional modulation was largest when dots competing for attention were placed within the same receptive field.

Therefore, a selection between object files that is determined by the need to reduce motion-signal ambiguity arising from nearby sources is proposed as an explanation of the data. Of importance, this selection could be taking place at relatively early stages of visual processing. When event-related potentials (ERPs) elicited by probes from attended and unattended surfaces similar to those used here were compared, P1 and N1 were virtually suppressed for the unattended but not for the attended surface (Valdes-Sosa, Bobes, et al., 1998). There is evidence implicating the human homologue of MT–MST in the generation of these ERP components (Anderson, Holliday, Singh, & Harding, 1996; Kubová, Kuba, Spekreijse, & Blakemore, 1995; Patzwahl, Elbert, Zanker, & Altenmüller, 1996; Schlykowa, van Dijk, & Ehrenstein, 1993), which is in agreement with functional MRI experiments that show modulation of activity in these same areas when attention is shifted between components of transparent motion (O'Craven et al., 1997; Watanabe et al., 1997).

The present experiments cannot establish whether signals from the unattended (invalidly cued) surface are suppressed, signals from the attended (validly cued) surface are enhanced, or a combination of both alternatives is present. A neutral cuing condition would be necessary for this. Nevertheless, the large suppression of ERPs in previous work with similar displays (Valdes-Sosa, Bobes, et al., 1998), the failure to even detect probes on the unattended surface, and participant reports that the unattended surface is seen as fainter all suggest that inhibitory processes may be involved. This point requires further work.

Several unique aspects of our displays could be responsible for results at variance with much previous work in attention. These displays represent ecologically valid situations (like monitoring predators partially hidden amid foliage). One aspect is the high spatial density of moving stimulus items. Another is that motion signals are monitored, signals that do not necessarily capture attention as could be the case for the abrupt pattern-onset stimuli used in many previous studies (Yantis, 1996). The other singularity is the use of long-lasting objects, which may have a different attentional status than objects that appear abruptly (see also Gottlieb, Kusunoki, & Goldberg, 1998). Finally, most studies of attention have been concerned with form processing and, ultimately, type identification (Kanwisher, 1987). Here motion processing and the monitoring of different object tokens was involved. The relative weight of each of these factors remains to be established in future work.

Concluding Remarks

Evidence is presented that attention cannot be divided efficiently between events affecting two components of transparent motion. This constraint cannot be explained by traditional spatial mechanisms (not even in a three-dimensional representation) or filtering based on simple sensory attributes. The effects depend critically on the parsing of the scene and the existence of separate object files to which the events were ascribed, and on the contiguity of the components of motion. Although the data yield evidence for object-based attention, avoiding criticisms leveled against previous demonstrations of this kind, the phenomenon demonstrated is not simply an inability to process two objects at once. It differs from phenomena traditionally studied in visual attention because interference is larger for stimuli that are closer in space, which might be due to several unique aspects of the displays used. The mechanism involved seems to be an early suppression of signals related to the unattended object file, which could serve the function of reducing receptive field information ambiguity.

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Attention to surfaces defined by transparent motion: measuring dwell time.

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Resumen:

Estudios recientes han demostrado que la atención puede ser dirigida selectivamente a un componente del movimiento transparente (Lankheet & Verstraten, 1995) y que no puede dirigirse eficientemente a dos componentes a la vez (Valdes-Sosa, Bobes, Rodriguez & Pinilla, 1998). En este trabajo estimamos el tiempo necesario para cambiar la atención entre dos superficies definidas por movimiento transparente. Para crear dichas superficies fueron utilizados dos conjuntos de puntos de diferente color que rotaban en direcciones opuestas alrededor de un punto de fijación. La distribución de la atención se determinó a partir de a discriminación de un evento consistente en un pequeño cambio en la dirección del movimiento de uno de los conjuntos. Dos eventos eran presentados sobre superficies diferentes, mediando entre ellos un tiempo variable. La discriminación del primer evento era priorizada, lo cual se reflejó en ejecuciones precisas para todos los tiempos entre eventos explorados. El segundo evento fue discriminado con precisión sólo para tiempos mayores de 450 ms. Estos resultados no se deben a limitantes espaciales en la división de la atención, dado que las dos superficies estaban superpuestas y muy próximas subjetivamente. Los resultados son consistentes con la atención basada en los objetos. El tiempo de transición estimado, alrededor de 450 ms, es similar a otras estimaciones basadas en la identificación de letras situadas en diferentes localizaciones (Ward, Duncan, & Shapiro, 1996).

Attention to Surfaces Defined by Transparent Motion: Measuring Dwell Time

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Recent work has shown that attention can be selectively directed at one component of transparent motion (Lankheet and Verstraten, 1995) and that it cannot be directed efficiently at two components at the same time (Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998). Here we estimate the time taken to switch attention between

two surfaces defined by transparent motion. Two sets of differently colored dots that rotated in opposite directions around fixation were used to create the surfaces. Discrimination of a brief change in direction of motion of one set was used to probe the distribution of attention. Two probes were presented on different surfaces with a variable SOA between them. Discrimination of the first probe was prioritized, which was reflected in an accurate performance for all SOAs. The second probe was accurately discriminated only for SOAs above 450 ms. These results are not due to spatial constraints on the division of attention, since the two surfaces were superimposed and in close subjective proximity. The results are consistent with object-based attention. The estimated dwell time of about 450 ms is close to previous assessments based on identification of letters placed at different locations (Ward, Duncan, & Shapiro, 1996).

Visual attention has been conceived as either selecting locations in visual space or as selecting higher level entities such as perceptual groups, objects, or surfaces (Egeth & Yantis, 1997; He & Nakayama, 1995). Evidence for object-based attention was reported by Duncan (1984) who found that two judgments concerning different properties of one object were just as accurate as single judgment. In contrast, interference was found when the two judgments concerned properties of different objects. More recent work indicates that attention lingers for hundreds of milliseconds on each object (Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996). The time that attention is trapped on one object has been designated attentional dwell time.

Transparent motion can be created when two sets of rigid dots transverse the same region of visual space, each moving in a different direction (Andersen & Wüestefeld, 1993; Qian, Andersen, & Adelson, 1994). This corresponds to the percept of two transparent surfaces sliding across each other. Each surface can be conceived as an "object." Lankheet and Verstraten (1995) have shown that attention can be directed selectively to one component of this type of transparent motion and therefore eliminate its contribution to the motion aftereffect. Another series of studies has shown that attention is divided poorly between two sets of dots generating transparent motion (Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998). This was ascertained by an effective suppression of P1 and N1 in the event-related potentials elicited by brief changes in the direction of motion of the nonprioritized set of dots.

Studies of attention to components of transparent motion are interesting since traditional space-based models of attention (Posner, 1980) have trouble handling selection of elements that are interspersed within the same visual region. Therefore, clear evidence for object-based mechanisms could be found with this type of display. Here we examine if switching attention between two surfaces defined by transparent motion takes as much time as switching between alphanumeric characters (Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996). The fact that the two surfaces are superimposed avoids the potential confound between locations and objects present in the previous experiments on dwell time.

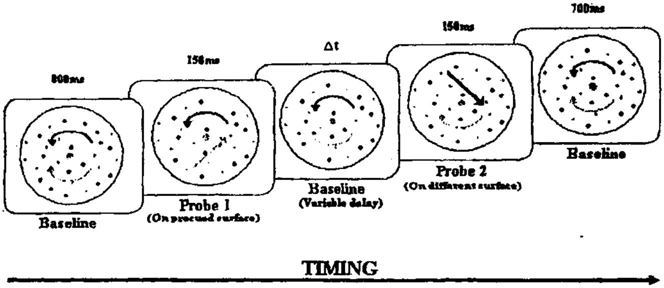

FIG. 12. The sequence of events in a trial. The background was actually black and dots were either red or an isoluminant green obtained by flicker photometry (represented as black or gray). The initial baseline rotations lasted 800 ms, and the final baseline rotations lasted 700 ms. Probe motions affected only one surface at a time and lasted 150 ms. The SOA between the two events was variable.

Methods

Two sets of dots, one red and the other green were used as stimuli. Each set consisted of 100 dots that were placed within an imaginary circle (6.9° diameter) that was centered on the fixation point, and which resulted in a dot density for each set of about 2.7/degree^2.

The sequence of events in a trial (Fig. 12) was as follows: First, the two sets of dots rotated rigidly around the fixation point in opposite sense (red dots rotated in clockwise, green dots rotated in anticlockwise sense) for 800 ms around the fixation point. This was the baseline. The speed of rotation was about 2.3°/s. Then a probe motion, consisting in a rectilinear translation in one of the cardinal or principal diagonals and lasting 150 ms duration affected one surface while the other surface continued rotating. The coherence of the motion was 60%. The speed of the translations was about 3°/s. After a variable delay, occupied by the baseline motion, the probe motion was presented on the other surface. A final baseline of both surfaces was continued until 700 ms after the offset of the last probe. The directions of the two probes in a trial were always different.

Ten participants were presented with one block of trials in a divided attention task. The participants were required to report both probe motions. Direction of motion was reported via the keyboard. At the beginning of each trial, the color of the fixation point indicated which surface would change motion first (the primary surface). The surface designated as primary on each trial followed a pseudo-random schedule. The instructions emphasized that maximum priority should be allocated to the primary surface.

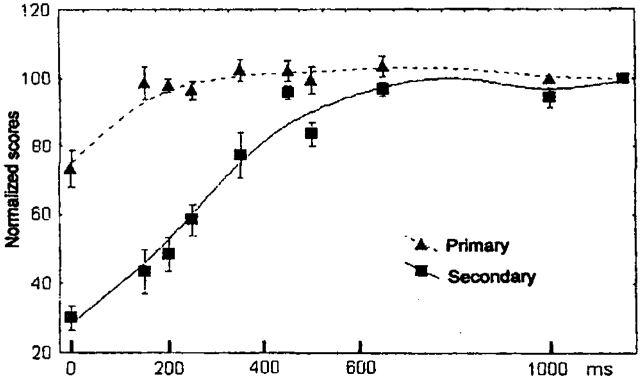

FIG. 13. Percent correct as a function of SOA and type of trial. Accuracy is plotted as a function of the duration of the SOA. The correct percent scores of each participant were normalized so that the value for the largest SOA corresponded to 100. Primary refers to responses made to the probe occurring first in time, which was also the most prioritized. Secondary refers to the second (and less prioritized) probe. Each data point corresponds to the mean of 10 subjects. The whiskers represent one standard error. The curves correspond to distance-weighted least square fits based on the means, with a stiffness of 0.25.

For four participants the between-probe stimulus onset asynchrony (SOA) used were 0, 200, 250, 350, 450, 650, and 1150 ms. For the other six the SOA used were 0, 150, 200, 250, 350, 500, and 1000 ms. At each SOA, 38 trials were presented. The order in which the SOAs were selected for each trial followed a pseudo-random schedule. Percent correct at each SOA for the primary and secondary response (collapsed across color) were calculated by participants, and these scores was normalized across participants by dividing each by the percent correct corresponding to the longest SOA in each individual.

Results

The group mean of the normalized accuracy scores is displayed as a function of probe SOA in Fig. 13. The direction of probe motion was discriminated with high accuracy when it concerned the primary surface, which reached an asymptote at a SOA of about 150 ms. In contrast, the accuracy of responses to probes affecting the secondary surface decreased monotonically as the SOA went from about 450 to 0 ms.

The curves that fit the data from each type of response are equivalent for

SOAs larger than 450 ms. This was confirmed by Student *t* tests with significant differences found between the accuracy scores related to primary and secondary surfaces for 0, 50, 200, 250, and 350 ms (with $p < 0.0003, 0.0019, 0.0001, 0.0001$, and 0.01, respectively).

Discussion

Interference of the judgments concerning the first surface on those affecting the second surface were found with SOAs up to about 450 ms. This can be seen as an upper limit to the attentional dwell time elicited by the conditions of the experiment. The estimate is close to similar measurements of attentional dwell time in letter detection tasks (see Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996). It is also consistent with the phenomenon known as the "attentional blink," in which the processing of a target in a rapid serial visual presentation (RSVP) interferes with subsequent detection of a second target for several hundred milliseconds (Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994). This relatively large persistence of interference is congruent with the view that attention need not involve a high-speed switching mechanism (but see Moore, Egeth, Berglan, & Luck, 1996, for a different interpretation).

The previous studies of attentional dwell time examined switches of attention between objects placed in different locations. Some doubt may arise as to how much of the dwell time is due to the need to change attention between locations. In this study, the use of transparent motion precludes the need to move the focus of attention in space. The dwell time therefore reflects a difficulty in changing attention from one object to another, even when these are placed in the same region of visual space.

All subjects reported the displays as quite flat and the two surfaces as very close to each other. Therefore, perceptual grouping was a more powerful constraint than spatial proximity in the division of attention. This supplies a clear demonstration of object (or surface) based attentional mechanisms.

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Attentional shifts between surfaces: effects on detection and early brain potentials.

Tupac Pinilla, Ariadna Cobo, Karina Torres y Mitchell Valdes-Sosa

Resumen:

Es posible discriminar fácilmente dos eventos consecutivos (cambios breves en la dirección del movimiento) que transforman la misma de dos superficies ilusorias creadas a través del movimiento transparente. Sin embargo, si ambos eventos ocurren en superficies diferentes se produce una prolongada interferencia (~500 ms) en la discriminación del segundo evento (Valdes-Sosa, Cobo & Pinilla, 2000). En este trabajo profundizamos en la caracterización de este fenómeno y lo comparamos con el 'parpadeo atencional' (PA -Shapiro, Raymond, & Arnell, 1994-). Al igual que en el PA, encontramos que cuando ambos eventos involucran superficies diferentes, se reduce la capacidad de detección (d') del segundo evento. Sin embargo, en contraste con lo reportado para el PA (Vogel, Luck & Shapiro, 1998), encontramos que existe una disminución en la amplitud del potencial cerebral N1 asociada al deterioro en la discriminación propio de cuando los eventos ocurren en superficies diferentes. Los resultados de este trabajo indican que la interferencia derivada del procesamiento de dos superficies diferentes se corresponde con efectos de competencia en la visión temprana. También se examinan las razones por las cuales se produjeron discrepancias con el PA.

Attentional shifts between surfaces: effects on detection and early brain potentials

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Running title: Attention to surfaces

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Abstract

Two consecutive events transforming the same illusory surface in transparent motion (brief changes in direction) can be discriminated with ease, but a prolonged interference (~500 ms) on the discrimination of the second event arises when different surfaces are concerned (Valdes-Sosa, Cobo & Pinilla, 2000). Here we further characterise this phenomenon and compare it to the attentional blink (AB, Shapiro, Raymond, & Arnell, 1994). Similar to the AB, reduced sensitivity (d') was found in the two-surface condition. However, the two-surface cost was associated with a reduced N1 brain response in contrast to reports for AB (Vogel, Luck & Shapiro, 1998). The results from this study indicate that the two-surface cost corresponds to competitive effects in early vision. Reasons for the discrepancy with the AB study are considered.

Keywords

Attention, Early vision, ERPs, Signal detection theory, surfaces, attentional blink

Introduction

Depending on the task, attentional selection can take place at different stages of processing. Lavie (1995) has proposed that selection operates at early stages only under conditions of high perceptual load. As argued by Luck and Hillyard recently (1999), the locus of attention depends on different processing stresses that determine in which cognitive subsystems selection is operating. The use of different experimental paradigms may therefore evince distinct types of attentional selection.

It has been firmly established (Hillyard & Münte, 1984; Mangun & Hillyard, 1988) that visuo-spatial attention (i.e. attending to certain locations) is reflected in a modulation of very early event related potentials (ERPs). The P1 and N1 components elicited by stimuli flashed at attended locations are enhanced relative to the same components elicited by stimuli placed at unattended locations. Most of the relevant experiments have been performed with attention sustained at one location for long periods of time, and with a high stimulus load (fast presentation rates).

Not infrequently we must shift attention within a natural scene from one location to another, or from one object to another, under conditions that vary in perceptual load. These situations can not be simulated by the classical sustained attention paradigm. More recently, other experimental designs in which attention shifts from trial to trial (and even within trials) have been employed. Several ERP studies (Mangun & Hillyard, 1991; Luck et al., 1994; Eimer, 1993, 1994a, 1994b) have used the spatial cueing paradigm developed by Posner (1980). They have found that stimuli at validly cued locations are associated with a larger P1 and N1, than is the case for stimuli at invalidly cued locations. However if the subject is asked to respond to all stimuli (valid or invalid) the modulation is smaller (Eimer, 1994b).

Another paradigm used to study selective visual attention is rapid serial visual presentation (RSVP), wherein streams of stimuli are flashed briefly at the same location. Several studies (Shapiro, Raymond, & Arnell, 1994; Duncan, Ward & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996) show that in RSVP recognition of one target (T1) produces a protracted interference in processing a subsequently presented target (T2). This phenomenon has been dubbed the 'attentional blink' (AB), in analogy with the brief interruption of information uptake during eye blinks. The AB results in failures of both discrimination and detection of the T2. A recent study by Vogel, Luck and Shapiro (1998) reports that the attentional blink is not associated with a suppression of P1 and N1, in contrast with experiments using spatial cueing (and sustained attention with fast stimulus rates). This suggest that selection in the AB corresponds to relatively late stages of processing. Therefore when attention shifts within a trial, the early ERPs may or may not be modulated according to the nature of the task demands.

After a long controversy (Duncan, 1984), agreement has been reached that visual attention can select either locations or objects (Luck, Woodman & Vogel, 2000). A recent study has shown that attention can be selectively directed towards one of two overlapped imaginary surfaces induced by transparent motion (Valdes-Sosa, Cobo & Pinilla, 1998). Note that the surfaces occupied the same region of space thus precluding spatial selection. In a subsequent study, imaginary surfaces were induced by rotating differently colored dots in opposite directions. Fast and long trains of brief changes in motion direction affected the two surfaces. Sustained attention to events on one surface produced a substantial suppression of the early P1 and N1 elicited by events on the other (unattended) surface (Valdes-Sosa, Bobes, Rodriguez & Pinilla, 1998). Therefore sustained selective attention to surfaces appeared to affect processing at an early stage, in the same way as described for sustained spatial attention.

We have recently developed a paradigm to study shifts of attention between the surfaces defined by transparent motion (Valdes-Sosa, Cobo & Pinilla, 2000). The task consisted of discriminating within each trial only two successive events of the type described above (brief changes in motion direction). The discrimination was accurate for both of the events when they affected the same surface independently of inter-event delays. In contrast, at short inter-event delays (below 600 ms) the discrimination of the second event (or T2) was poor if it affected a surface different from the first (T1). This two-surface cost seems to reflect a difficulty in switching attention rapidly between surfaces, and occurred despite the spatial superposition of the two surfaces. We will call this phenomenon surface dwell-time (SurfDT).

SurfDT and the AB have interesting similarities. The paradigm eliciting SurfDT is formally similar to that eliciting the AB, especially the "minimal" RSVP variant which does not use distracters (Egeth & Yantis, 1997; Duncan, Ward & Shapiro, 1994). In both phenomenon, recognition of T1 hampers processing of a subsequently presented T2. The duration of the AB and SurfDT is also similar. However, we do not know if the processing constraints revealed by the two phenomena are the same or be different and further comparisons are warranted.

In the present study we compare the AB and SurfDT in two respects. The AB produces both detection and discrimination deficits on T2 when T1 is attended. To extend previous work establishing discrimination deficits during the SurfDT, here the detection of events on the unattended surface was studied with a signal detection paradigm. Moreover, the effects of SurfDT on ERPs were also studied, to determine if P1 and N1 are modulated when attention shifts between surfaces thus revealing early attentional selection, or if these components are unaffected (as reported for the AB) indicating that late selection is involved.

Experiment 1

The problem of whether attention affects the quality or strength of sensory signals has been addressed before with detection paradigms in the context of the debate between 'early' and 'late' spatial-attentional selection. Bashinski & Bacharach (1980) were the first to report a reduction of d' for the detection of faint luminance changes at uncued locations, a finding that has been replicated in other studies (e.g. Reinitz, 1990).

One problem with the initial attempts to apply signal detection theory in spatial cueing paradigms (discussed in Downing, 1988 and Luck et al., 1994) was the ambiguity in assigning false alarms to either the cued or the uncued location. To solve this problem, post-cue signals have been used, to query for detection at specific locations on each trial. Significant effects of cue validity on d' have also been found applying this approach (Downing, 1988, Müeller & Humphreys, 1991; Hawkins et al., 1990; Luck et al., 1994).

The goal of this experiment was to examine if attention to one transparent surface reduced the capability to detect motion in another surface, in addition to the discrimination costs already described in previous articles. The paradigm was the same used in previous reports of SurfDT (Valdes-Sosa, Cobo & Pinilla, 2000), with the exception that a 'yes/no' motion-detection response was required for the second event-motion in place of the discrimination task. The experiment was performed twice. In the first replication, false alarms were not assigned to a particular surface. In the second replication the post-cue design described above was adapted in order to assign false alarms to one of the two surfaces.

Method

Participants

Personnel from the Cuban Center for Neuroscience, all university graduates, participated in the experiments reported in this article. Their age range, sex distribution, and handedness are described in Table 1. All the subjects had normal or corrected-to-normal visual acuity, reported no color vision abnormalities, and had no history of neurological disorders.

Stimulus material

Visual stimuli were presented on a sVGA monitor with a black background. A small circle of 28 arcmin diameter was placed at the center of the screen as a fixation point. The stimuli consisted of two interspersed sets of moving dots (100 dots each). The dots were 1 pixel in size and initially drawn at randomly selected locations within an imaginary circle (diameter of about 6.9 degrees) centered on the fixation point. Each set moved in a different direction (see fig. 1). Heterochromatic flicker photometry was used for each participant, to obtain a green that was equiluminant with the maximum intensity of red. Each set of dots was assigned one of the two colors thus defined.

Two types of motion were used: baseline and event motion. In Figure 1 the structure of the different types of trials is described. The baseline motion consisted of rigid rotation around the fixation point. The speed of rotation was about 40 degrees/s of angular speed. Linear displacements in the cardinal and diagonal directions were used as events (eight alternatives), moving at a speed of about 3 degrees/s. The event motion was 60% coherent (see Valdes-Sosa et at, 2000 for a more detailed description).

Procedure and design

Participants initiated each trial by pressing the space bar of the computer keyboard. The color of the fixation circle forewarned which of the two surfaces was to be affected by the first event. Then stimulus motion began after a 500 ms delay, followed by an 800 ms baseline period in which the two sets of dots rotated in opposite directions (see Figure 1). Then an event lasting 150 ms affected the cued surface while the other surface continued to rotate. After this both surfaces rotated in the baseline pattern for 350 ms. Then a second 150 ms event was presented, followed by an additional 800 ms rotation period. The direction of the two events was always different.

The experiment was performed in one session, which consisted of 192 trials. The first event affected each set of dots on half the trials. On 96 of the trials, only the first event was presented in each trial. On the other 96 trials, two events were presented within each trial. The events affected the same surface in half of two-event trials, whereas different surfaces were involved on the other half. Thus, there were six possible combinations of events, two for the single-event trials (red-null, green-null), two for the same-surface trials (red-red, green-green), and two for the different-surface trials (red-green, and green-red).

At the end of the trial the participants were required to report the direction for the first event motion on the numerical-pad of the computer keyboard. They were then required to respond on one key if they had detected a second event-motion (and on another if they had not). In Experiment 1A, the participants were asked to respond 'yes' if they perceived any motion without reference to the surface on which it could have occurred. In Experiment 1B the query about the second motion was always referred to a specific set of dots (e.g. 'did the red dots move?'). In the case of two event-trials, the question was always asked of the surface on which the second event had affected (see Luck et al., 1994 for a similar design). When only one event was presented, on half of trials the question was asked for the affected surface, and on the other half about the other surface.

The percentage of correct responses to the first event, as well as the Hits (saying 'yes' when a second event-motion had occurred) and False Alarms (saying 'yes' when the second event was absent), was obtained for each type of trial, in all participants. In Experiment 1B the false alarms were calculated separately for responses concerning the same surface on which the first event occurred, and for responses related to a different surface. Since the color of the dots did not produce any significant effect in subsequent analysis, data were also collapsed over this factor. The percentage of Hits and False Alarms were used to calculate the d' and logarithm of Beta (log-Beta) measures of Signal Detection Theory in each participant for the second event for each type of trial (Green, & Swets 1966).

Results and Discussion

Mean accuracy in discriminating the direction of the first event-motion was 84% (range across participants 73-92) in Experiment 1A and 90 % (range 76-94) in Experiment 1B. The mean Hit rate was larger on same-surface trials than on different-surface trials (Table 2) in both experiments. These effects were significant, in both Experiment 1A, $t(6)=2.7$, $p<0.036$, and in Experiment 1B, $t(9)=3.6$, $p<0.006$.

In Experiment 1B where separate estimates were available the False Alarms were roughly equivalent for the two types of trial. In both experiments, the mean d' for same-surface trials was also larger than for different-surface trials, $t(6)=5.16$, $p<0.002$ for Experiment 1A and $t(9)=3.6$, $p<0.006$, for Experiment 1B. Despite the lower mean d' for the different-surface trials, in both experiments this value was significantly larger than zero ($p<0.002$). The mean log-Beta scores in the same-surface trials were significantly more negative than in different-surface trials in both experiments, $t(6)=3.5$, $p<0.013$ and $t(9)=2.6$, $p<0.03$, for Experiments 1A and 1B respectively.

More positive Log-Beta (or equivalently larger Beta) values were found in the different- compared to the same-surface trials. Similar effects on Beta have been reported in spatial cueing tasks (Downing, 1988; Luck et al., 1994; Müeller & Findlay, 1987; Müeller, 1994), with larger values for uncued compared to the cued locations. More conservative criterion would correspond to uncued locations because there is a low 'a-priori' probability of targets being presented there (Müeller & Findlay, 1987; Müeller, 1994). In our case the 'a priori' probability of presenting a target on the same or on a different surface as the first event was equal. However, if the participants 'missed' many of the events on the different-surface trials, this could lead to a low perceived relative-frequency for this type of event and therefore decisions that are more conservative. This idea is supported by a significant correlation across participants in Experiment 1B between d' and Log-Beta for the different-surface trials, $r=0.76$, $t(9)=3.3$, $p<0.011$, but not for the same-surface trials.

The results from the two replications of the experiment are in complete agreement which each other. They indicate that when an event on one transparent surface captures attention, the detection of a rapidly following second event is hampered if it occurs on a different surface. This effect was measured by the d' measure which is free from the contamination of criterion variation (Green & Swets, 1966). Similar results have described in spatial cueing tasks, for the detection of luminance decrements (Bashinski & Bacharach, 1980), luminance increments (Downing, 1988; Hawkins et al 1990; Müeller & Humphreys, 1991, Luck et al, 1994), as well as brightness, orientation, and form discriminations, (Downing, 1988). This extends previous findings (Valdes-Sosa, Cobo & Pinilla, 2000) and show that both discrimination and detection are affected when attention must switch from one surface to another at short notice.

Experiment 2.

The previous study shows that SurfDT, like the AB, is associated with a deficit in detection and not only a difficulty in discrimination. In this experiment, we examine whether the early visual ERPs are affected during the SurfDT. If SurfDT behaves in similar fashion as reported for the AB (Vogel, Luck, & Shapiro, 1998), it should have little effect on these ERPs. With this aim in mind, the paradigm used in previous reports of SurfDT (Valdes-Sosa, Cobo & Pinilla, 2000) was adapted for ERP recording. The onset of event motion was used as a trigger for the signal averaging used to estimate the ERPs. Several groups (Göpfert, Muller & Simon, 1990; Kuba & Kubová, 1992a, 1992b; Bach & Ullrich, 1994) have studied the ERPs elicited by motion-onset or changes in motion direction, in particular the first negative component, N1 (or N200). Recent experiments have shown that attention clearly modulates early components of the motion-onset ERPs, including N1 in other paradigms (Valdes-Sosa, Bobes, Rodriguez & Pinilla, 1998; Torriente, Valdes-Sosa, Ramirez & Bobes, 1999).

Method

The method was the same as in Experiment 1, except as described in the following. Participants were asked to report the direction of dominant (coherent) motion for both events described for Experiment 1. Event duration was restricted to 100 ms, thus the inter-event SOA was 450 ms.

The same three types of trial as in Experiment 1 were used: same-surface, different-surface, and single-event trials. Thus there were six possible combinations of events, two for the single-event trials (red-null, green-null), and two for the same-surface trials (red-red, green-green), and two for the different-surface trials (red-green, and green-red). For each of these conditions 200 trials were presented in the whole session.

The procedure was identical to that of previous experiments (Valdes-Sosa, Cobo & Pinilla, 2000). Additionally, the subjects were instructed to maintain fixation, and minimize body movements and eyeblinks during recording blocks. The session was divided into five blocks. The participants rested for a few minutes between blocks.

The percentage of correct responses to the first and second events was obtained for each type of trial, with data collapsed over blocks, in all participants. Since the color of the dots did not produce any significant effect in subsequent analysis, data were also collapsed over this factor. The percent correct scores were submitted to a rm-ANOVA with event-sequential-order (first vs. second) and number-of-surfaces (same-surface vs. different surface) as main effects.

Electrophysiological Recording

Electrophysiological data acquisition and analysis were carried out on a MEDICID 3E (Neuronic SA) system. Disk electrodes (Ag/AgCl) were placed with electrolytic paste on 8 active derivations (Pz, Oz, P3, P4, T5, T6, O1, and O2) of the 10/20 international system. All active electrodes were referred to linked earlobes. Inter-electrode impedance was always kept below 5 kOhms. Bipolar derivations were used to record the EOG, with electrodes just lateral to the external canthi for the horizontal movements and 1 cm above and below the right eye for the vertical movements. The signals were filtered between 0.05-70 Hz (3 dB down). Additionally, a notch filter with peak at the power line frequency was used. In each trial, marks corresponding to events (linear motion onset) were co-registered with the amplified and digitized EEG (12 bit resolution), which was sampled at a rate of 250 Hz, and stored on magnetic disk for off line analysis.

The continuous EEG record was windowed with a pre-stimulus baseline of 100 ms before pattern-onset, and a 700 ms post-stimulus epoch. Each EEG segment was visually inspected and trials with artifacts or excessive activity in the EOG were rejected. This eliminated from about 1 % to 19 % of all stimulus events across conditions, which resulted in individual ERPs based on the average of about 162 to 198 events (collapsed over color in the following, since this factor was not significant in subsequent analysis). For every subject, averaged ERPs synchronized with event motion-onset were obtained for all recording sites, for each stimulus condition.

Since a short SOA was used in the two event trials, the ERPs elicited by the first event overlapped and distorted those related to the second event, which were the center of interest. The isolated responses related to the second event were estimated by subtracting in each individual the ERPs from the one-event trials (which contained only responses to the first event) from ERPs associated either to same-surface, or different surface trials. Grand average ERPs and difference waveforms were calculated for all groups of Ss for each site and condition. All data points were corrected (prior to plotting or measurement) by subtracting the average pre-stimulus amplitude value.

The attention effects were tested by two statistical procedures. The first, more traditional method was based on measuring the average amplitude of two time windows (corresponding to the P1 and N1 elicited by the second event). The measures were obtained from the difference waveforms at all sites; for each individual. The time windows were for P1 from 110 to 190 ms and for N1 from 240 to 330 ms. Separate rm-ANOVAs were performed for each component. Number-of -surfaces (same-surface vs. different-surface), electrode-site (temporal vs. occipital) and electrode-laterality (right vs. left), were the main effects in the ANOVA for P1 and N1. Number-of -surfaces and site (three levels) were the main effects in the ANOVA for P2. To examine scalp topography, an additional rm-ANOVA was performed for N1 with data from the eight active electrodes, with number-of-surfaces and electrode as main effects.

Recently, computer-intensive methods based on permutation principles have been proposed as an alternative statistical methodology for testing differences between ERPs (Blair & Karniski 1993, 1994; Galán et al., 1997). Non-parametric permutation techniques were used in the second statistical procedure. The global null hypothesis tested was the equality between the ERPs associated with same- and different-surface trials at all electrode derivations and for all time points. The marginal null hypothesis was the equality of the ERPs at each particular time points at any given electrode site. This procedure allows the location and timing of the effect to be located more precisely.

Results and discussion

Behavioral data

The accuracy in the direction judgment task is shown in Figure 2. The first direction discrimination was very accurate for all conditions with no significant differences between the corresponding mean scores. The second discrimination was less accurate, although large decreases in performance were present only for the different-surface condition. The drop in accuracy from the first to the second discrimination was only about 10% when the events were on the same surface. The drop from the first to the second event was about 45% when they were placed on different surfaces.

These results were reflected in highly significant effects in a rm-ANOVA of event-sequential-order, $\underline{F}(1,9)=138.8$, $\underline{p}<0.00001$, and number-of-surfaces, $\underline{F}(1,9)=63.2$, $\underline{p}<0.00002$, as well as the interaction between the two factors, $\underline{F}(1,9)=109.0$, $\underline{p}<0.00001$. The interaction reflects that whereas the first discrimination was not affected by of the number of surfaces involved, the judgment corresponding to the second event was significantly less accurate for the different-surface condition than for the same-surface condition, $\underline{F}(1,9)=92.3$, $\underline{p}<0.00001$.

The results indicate very little interference for judgments on the second event when it was placed on the same surface as the first event. In contrast, in the different-surface task case, where attention had to switch between surfaces, a large deterioration of performance for the second stimulus was obtained. These results replicate previous work (Valdes-Sosa, Cobo & Pinilla, 2000), and strengthen the conclusion that under certain conditions there is a limit to the number of events from different objects that can be attended to within a short period of time.

ERP data

The grand average ERPs corresponding to the different conditions, used in the experiment, are displayed in Figures 3 and 4A. Two sequential and distinct responses were observed in the original waveforms when the two events were presented. The response to the first event did not differ between conditions and will be ignored.

Several peaks (described in order of peak latency) were present in most participants in the difference waveform that isolated the response to the second event. These were P1, largest at occipital sites; N1, largest at posterior temporal sites and finally the P2 that was largest at Parietal sites and that will not be considered further. Information on the latency of these peaks is shown in Table 3. See Figure 4B where the scalp distribution of N1 is presented in the same-surface condition.

There was no clear effect of the number-of-surfaces in the P1 time window. The only significant effect on P1 amplitude was that of electrode-laterality, $\underline{F}(1,9)=5.15$, $\underline{p}<0.05$, with amplitudes on the right side twice as large as on the left (0.2 µV vs. 0.4 µV). Therefore attentional effects were not found here for P1. However, before concluding that SurfDT does not affect P1 two aspects must be considered.

The P1 was very small in this study and dominated by the subsequent N1. Bach and Ullrich (1994) have demonstrated that when the motion duty-cycle (the amount of time that the relevant motion is present relative to when it is absent) is short, then N1 dominates the motion-onset ERP. Event duty-cycle here was short (if rotations and stationary conditions are lumped together). Furthermore, it is possible that the perceptual load in this study was insufficient. Psychophysical evidence suggests that attentional effects are earlier as the perceptual load is increased (reviewed in Lavie & Tsal, 1994). In a sustained attention experiment using stimuli similar to those used here, a higher perceptual load (faster event presentation rate), and a longer motion duty-cycle were used. A strong suppression of the P1 elicited by events on the unattended surface was found (Valdes-Sosa, Bobes, Rodriguez & Pinilla, 1998). Further research on this is necessary.

The N1 was substantially attenuated when it was on a different surface than the first event. This can be seen more clearly in the difference waveforms, where the contribution from the response to the second event is isolated (Figure 3 and 4A). The rm-ANOVA confirmed this observation. In the rm-ANOVA for N1 amplitudes at posterior sites, the effect of number of surfaces was significant, $\underline{F}(1,9)=9.14$, $\underline{p}<0.014$, with a mean value of 1.9 µV for the same-surface condition and of 0.7 µV for the different-surface condition. Electrode-site and electrode-laterality were not significant.

In the rm-ANOVA on N1 amplitudes from all sites, number-of-surfaces, $\underline{F}(1,9)=4.8$, $\underline{p}<0.06$ was marginally significant, and electrode, $\underline{F}(7,63)=4.2$, $\underline{p}<0.009$, $\varepsilon=0.3$, and the interaction of the two factors, $\underline{F}(7, 63)=4.5$, $\underline{p}<0.004$, $\varepsilon=0.26$, were significant. However, after normalizing the amplitude measurements as recommended by McCarthy and Wood (1985) for testing with ANOVAs effects on the scalp topography of ERP components, the interaction of number-of-surfaces with site was not significant, $F(7, 63)=1.1$, $p>0.3$, $\varepsilon=0.4$. This indicates that the amplitude change of N1 as a function of attention was not associated with a change neither in scalp topography nor in latency.

In order confirm the results just described and to better determine the onset latency of the attentional effect, the ERPs associated with same- and different-surface trials were compared with t-tests (corrected by the use of permutation techniques at each time point. The two ERPs were different in the global test, $p<0.02$. The earliest difference between conditions was detected at the T6 electrode site, at a latency of 171 ms after the second event with a $p<0.036$. The effect in that site was significant at the 0.001 level from 190 to 277 ms, and the last significant point was at 280 ms, at the 0.05 level. These time limits overlap with those of the N1 component.

Summarizing, when the subjects had previously engaged their attention on a surface, the N1 elicited by an event on that surface was significantly larger than when the event affected the other surface. The variation of N1 associated with attention did not produce changes in the topography of the component, nor important changes in its latency. The relatively early latency of this effect and the absence of topographic changes differentiate it from attentional selection negativities described by previous reports (Anllo-Vento & Hillyard, 1996).

The N1 attentional effect described here is similar to that found for the N1 elicited by sudden-onset stimuli in spatial cueing tasks (Mangun & Hillyard, 1991; Eimer, 1993; 1994a; Luck, et al., 1994). This type of effect has been considered to be a hallmark of spatial attention. In agreement with our previous reports (Valdes-Sosa, Bobes, Rodriguez & Pinilla, 1998; Torriente, Valdes-Sosa, Ramirez & Bobes, 1999), the present experiment shows that motion-onset ERPs can be modulated also by object-based attention in the absence of spatial displacements of the focus of attention. However, the N1 described here is of longer latency (260 ms) than what is typical of the N1 elicited by sudden-onset stimuli which is about 180 ms. This may create some doubts on how to interpret the result, and this problem is addressed in the next experiment.

Experiment 3

The N1 elicited by events in Experiment 2 peaked about 80 ms later (at 260 ms) than what is typical for the N1 in studies of visuo-spatial attention, or in the study of the AB by Vogel, Luck and Shapiro (1998). The N1 elicited by sudden-onset patterns in studies of spatial attention ranges in post-stimulus latency from about 150 to 200 ms (for a review see Näätänen, 1992). At first glance, this seems to indicate a later locus for attentional influence during the SurfDT than for spatial selection. However, the latency of any ERP component is influenced by many stimulus factors such as the luminance or contrast. Here we examine one stimulus factor that can influence the latency of the motion-onset ERP, adaptation to a previous period of motion.

The N1 elicited by the motion-onset of previously stationary patterns usually has a shorter latency, at about 180 ms (Göpfert, Muller & Simon, 1990; Kuba & Kubová, 1992a, 1992b; Bach & Ullrich, 1994; Torriente, Valdes-Sosa, Ramirez & Bobes, 1999). However, the events in the present study were presented after a period of background rotational motion. A recent study shows that the amplitude and latency of the N1 elicited by motion-onset are respectively reduced and delayed after pre-adaptation by a previous period of motion stimulation (Muller, Göpfert, Breuer, & Greenlee, 1998-1999). Therefore, the latency values of N1 here may be reflect sub-optimal stimulation conditions related to this motion pre-adaptation.

Methods

The method was the same as in Experiment 2, except as described in the following. Only five subjects were recorded. Only single event trials were used (see Figure 1). Events lasted 100 ms . The speed of the baseline rotational motion was randomly selected among four alternatives: 0, 20, 40 and 80 degrees/s of rotation for each trial. This corresponds to a stationary background, and to rotational motions that were half, the same, and twice as fast as the rotation in Experiment 2. 120 trials were presented using each background speed. The ERPs elicited in trials with these different background speeds were averaged separately.

Results and discussion

The latency of N1 was shortest when the background was stationary and increased monotonically as the speed of the background rotation was increased. This can be observed in the grand average ERPs (Figure 5A) recorded at electrode sites T6, and the plot of the corresponding mean peak latency of N1 for each condition at T5 and T6 (Figure 5B). The effect of background speed was significant in a rm-ANOVA including the measures in Figure 5, $\underline{F}(3,12)=22.6$, $\underline{p}<0.001$, $\varepsilon=0.6$. The effect and interaction involving electrode site (T5 vs. T6) were not significant. A contrast analysis showed a significant linear trend, $\underline{F}(1,4)=45.0$, $\underline{p}<0.003$. The shift in latency as a function of background speeds ranged over 60 ms and for the speed used in Experiment 2 the latency shift respect to the stationary background would have been about 41 ms at T6.

These results indicate that the relatively long N1 latency found in Experiment 2 can be explained in part by the effect of a moving background period. In fact, this latency shift could correspond to visual motion adaptation. The magnitude of the adaptation effect was probably underestimated in the present experiment, since only the first events were presented after 800 ms of baseline rotation, whereas the second events in Experiment 2 were presented after 1250 ms of motion (see figure 1). The implication of these findings is that the N1 that is modulated by attention in the present study corresponds to a component that under optimal stimulation conditions would typically have a latency of about 190 ms.

General Discussion

In Experiment 1, large reductions of the sensitivity for detection of an event affecting an unattended surface were found relative to detection of events affecting the attended surface. This demonstrates that SurfDT hampers both discrimination and detection of events. In Experiment 2, the N1 elicited by the second events were reduced in amplitude during the different-surface trials as compared with the same-surface trials. Suppression was already significant as early as 170 ms after the event. The third experiment suggests that N1 latency here was prolonged due to motion adaptation, and that this latency with a stationary background would be at least 40 ms shorter.

As mentioned before d' is considered to reflect perceptual processes, uncontaminated by guessing, or output biases. Therefore, the reduced d' associated with SurfDT is not explainable by changes in the subjects response criterion, or guessing strategies. The fact that SurfDT is related to both discrimination and detection deficits is another point of similarity to the AB in addition to its long temporal course (both near 500 ms).

Our previous study (Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998) evinced a strong suppression of both the P1 and N1 for events affecting the unattended surface, when the perceptual load was very high (fast event presentation rate) and attention was sustained on one surface for several minutes. In the present study we show that the relative suppression of N1 is also related to the sluggish shift of attention from one surface to the other within the same trial, providing converging evidence for early selection in the SurfDT.

This result is also in line with the spatial cueing ERP studies, where larger sensory-evoked responses are observed for targets on validly cued positions than on invalid ones, reflecting an enhancement of sensory processing. However, there is one interesting discrepancy. In trial-by-trial spatial cueing tasks, when both validly and invalidly cued stimuli required a response, the early ERP modulations is smaller than when responses are only required for the valid stimuli (Eimer, 1994b). This indicates that asking for responses to invalidly cued stimuli favours attentional reallocation (perhaps by faster shifts of attention) within a trial.

Here, subjects were asked to respond to events affecting both the attended and unattended surface. Despite this, modulation of early components is obtained. Also in a previous study (Cobo, Pinilla & Valdes-Sosa, 1999) found that the duration of SurfDT was unaffected even when subjects had foreknowledge about the need and the direction of an attentional shift (e.g. from red to green or vice versa). This indicates that suppression due to SurfDT is possibly more stronger than in spatial cueing tasks and less subject to strategic control. The superposition of the two surfaces in transparent motion may have to do with this finding. A recent model has argued one of the functions of attention is to reduce ambiguity within receptive fields (Luck et al., 1997). In transparent motion, the degree of ambiguity to reduce may be larger than in spatial cueing experiments.

The finding of a N1 modulation associated with SurfDT indicates a difference of this phenomenon from the AB. In a previous study (Vogel, Luck & Shapiro, 1998) the AB is not associated with variations of P1 or N1 amplitudes, therefore concluding that the AB reflects a relatively late suppression of information. In that case the AB and SurfDT could arise at different processing stages. Nevertheless before accepting this conclusion, a potential problem with the irrelevant-event technique used in the mentioned study must be considered.

ERPs recording in RSVP is complicated by the overlap of signals caused by the fast-paced successive stimuli. To solve this problem for the study of the AB, Vogel, Luck and Shapiro (1998) introduced one irrelevant-event on certain runs of RSVP at a certain temporal position that varied over runs. The irrelevant-events were bright squares flashed behind the second target. Subtraction of the ERPs associated to runs without events from runs with events should isolate the response triggered by the event. The rationale is that the amplitude of the P1 and N1 should reflect attentional modulations within the visual system as a function of time. They found that despite substantial impairment of accuracy in discriminating the T2 at certain times within the RSVP run, there was no suppression of the P1 and N1 elicited by the corresponding irrelevant-events compared to events presented at times with no interference.

A relatively salient event (pattern-onset and luminance-increment), is capable of attracting attention automatically (Yantis & Jonides, 1990). The event may be irrelevant but it is not unobtrusive. An automatic attentional-capture by the probe could mask effects of the AB on the ERPs. The motion events used in our study do not capture attention to the same degree as sudden-onset stimuli (see Yantis & Hillstrom, 1994). Further studies of the AB with the irrelevant probe technique are necessary, but with probes that are milder attention-grabbers. If the distinction between the AB and SurfDT is maintained, then we would have two paradigms that evince different mechanisms of selective attention. This opens the possibility that attention can 'blink' in different ways.

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Figure Legends

Figure 1. Sequence of stimulus events in a trial: The background was actually black, and dots were either red or green isoluminant with the red (represented as black or gray). The color of the fixation point pre-cued the surface to be attended, where the first event would occurred. A) Events in same-surface trials: both events affected the same pre-cued surface. B) Events in different-surface trials: the second event affected the uncued surface, different from the one affected by the first pre-cued event. C) Events in single-event trials: only the first event took place affecting the pre-cued surface. Note that event (and therefore SOA) duration was different in experiments 1 and 2.

Figure 2 Percent Correct in Experiment 2 as a function of distribution of attention and event sequential order: The ordinate axis represents the sequential order in which the two events were presented. Each line represents a different type of trial. In the same-surface trials both events affected the same pre-cued surface. In the different surface trials the second event affected the un-cued surface, which was different from the one affected by the first pre-cued event. Each data point corresponds to the mean of 10 subjects. The whiskers represent one standard error.

Figure 3 ERPs obtained in Experiment 2: Grand averages of the ERPs elicited by event onset (for the 10 subjects) from right posterior temporal region (T6), for each type of trial: A) Two events on same surface; B) Two events on different surfaces; C) Only one event. The large vertical line corresponds to moment of the second event presentation. Ticks correspond to 200 ms marks. The P1 response is smeared respect to the ERPs from individuals. The responses related to the second event were isolated by subtracting the ERPs from the one-event trials from ERPs associated either to same-surface (D), or different-surface trials (E). Positive points up.

Figure 4: A) Grand average difference waveforms from Experiment 2, with the isolated response to the second event. Responses to same- (cued) and different- (uncued) surface trials are overlaid. The time axis is referred to the onset of the second event. Positive points up. The two arrows indicate times when events were presented. B) Average amplitude (with baseline corrected) of N1 as a function of site (same locations as in A) and side of the scalp. The measure was obtained for the same-surface condition and for the time window defined in the text. Each data point corresponds to the mean of 10 subjects. The whiskers represent one standard error.

Figure 5: A) Grand Average ERPs from T6 in Experiment 3. Each row corresponds to a different background speed of rotation. The arrows indicate the N1 peak latency. The amplitude decreases and the latency increases for larger rotation speeds. B) The mean peak latency measured at T5 and T6. Each data point corresponds to the mean of 5 subjects. The whiskers represent one standard error.

Tables

Table 1 Characteristics of the Participants by Experiment.

Experiment	Age Range	Sex		Handedness	
		Females	Males	Right	Left
1A	21-28	3	4	7	0
1B	21-29	9	1	9	1
2	24-43	1	9	9	1
3	24-30	2	3	5	0

Table 2 Sensitivity for the detection of a second event in Experiment 1 for same-surface and different-surface trials.

Experiment 1A	% Hits	% FA	d'	Log β
Same	94 (6)	20 (14)	3.32 (1.4)	-1.4 (2.0)
Different	73 (25)	"	1.92 (1.1)	0.0 (1.2)
Experiment 1B				
Same	94 (5)	11 (7)	3.7 (1.3)	-0.8 (1.8)
Different	69 (26)	15 (9)	2.1 (1.5)	0.7 (2.0)

Notes: Means and standard deviations (the latter between parenthesis) are indicated. Same and different rows refer to the surface on which the second event was placed in relation to the first event. In experiment 1A there was only one common estimate of false alarms (FA) for the two conditions.

Table 3 Mean (M) and standard deviation (SD) of the ERP peak latencies across participants in Experiment 2 in the difference waveform that isolates the response to the second event.

	P1	N1
M	130	262
SD	40	33

Note: Each estimate is based on 10 participants and measured at T6.

Fig. 1

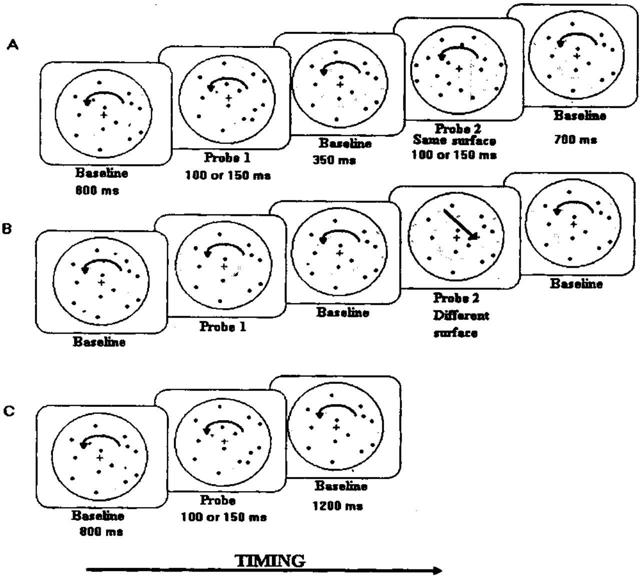
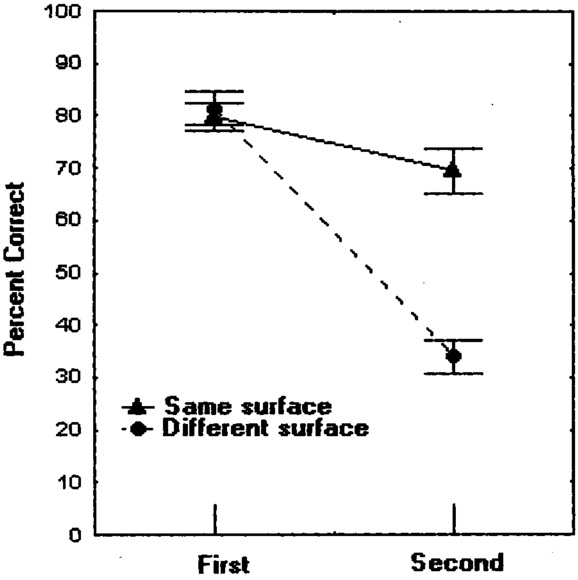

A
Baseline
800 ms
Probe 1
100 or 150 ms
Baseline
350 ms
Probe 2
Same surface
100 or 150 ms
Baseline
700 ms
B
Baseline
Probe 1
Baseline
Probe 2
Different
surface
Baseline
C
Baseline
800 ms
Probe
100 or 150 ms
Baseline
1200 ms
TIMING

Fig. 2


100
90
80
70
60
50
40
30
20
10
0
Percent Correct
Same surface
Different surface
First
Second

Pinilla et al., Attention to surfaces Fig. 3

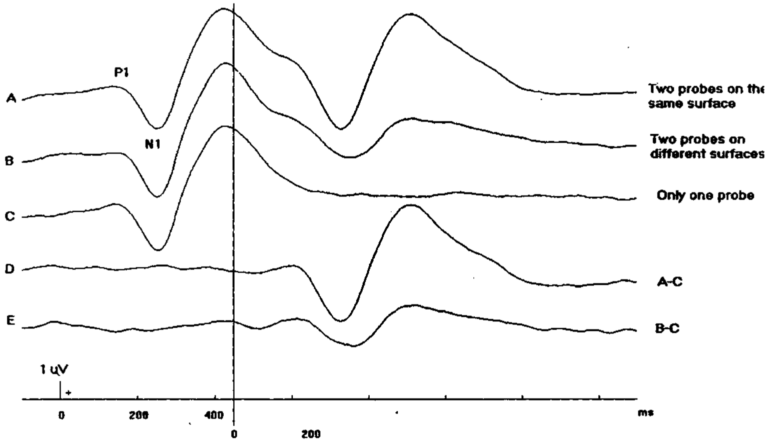


Fig. 4

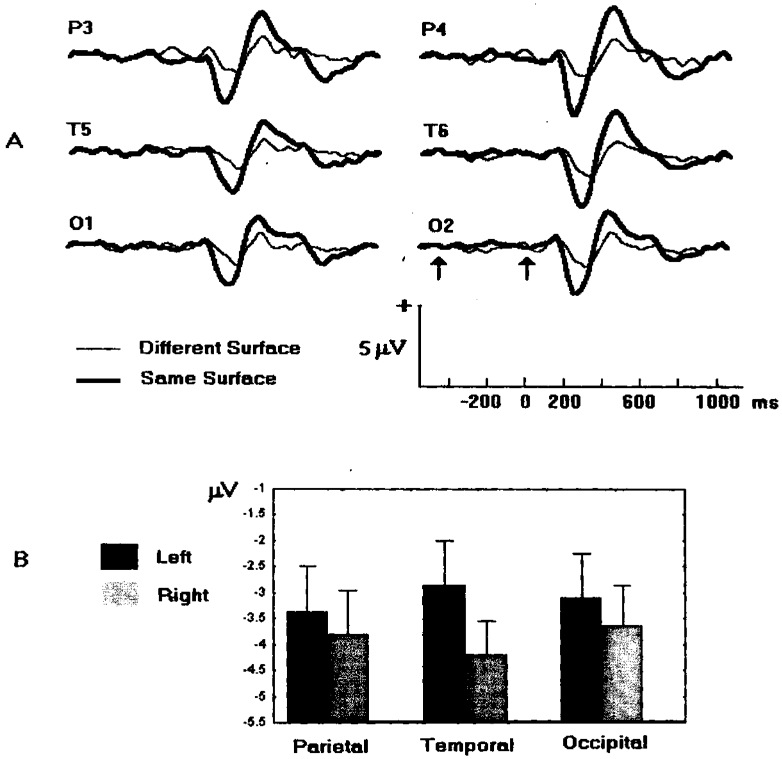
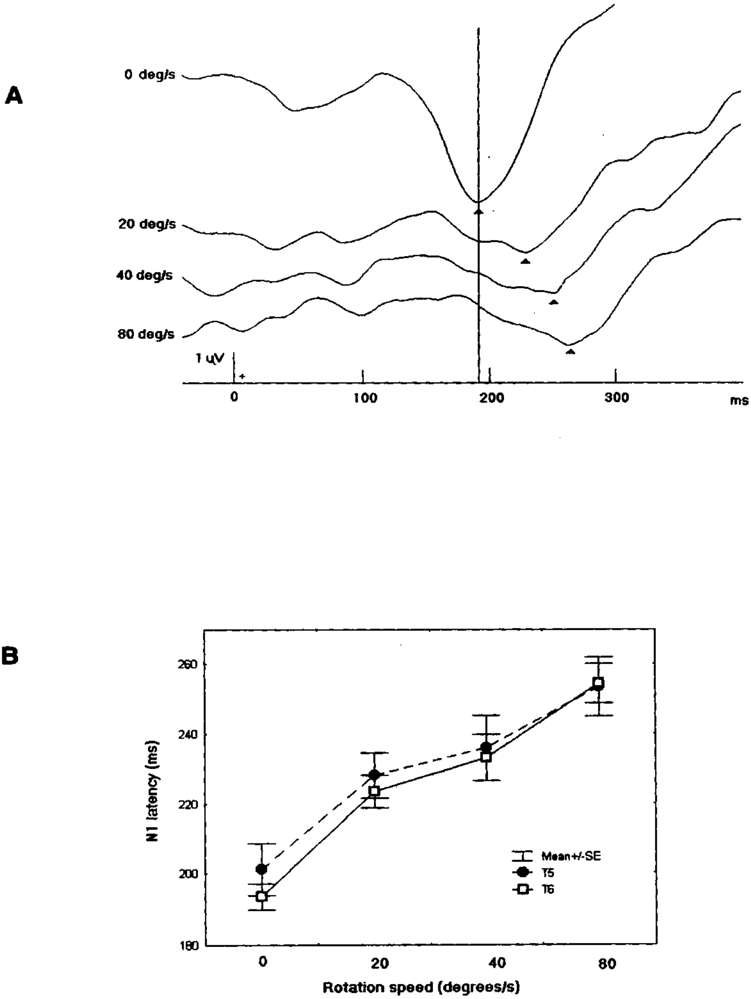

A
P3
P4
T5
T6
O1
O2
Different Surface
Same Surface
+
5 µV
-200
0
200
600
1000
ms
B
Left
Right
µV
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
Parietal
Temporal
Occipital

Fig. 5


A
0 deg/s
20 deg/s
40 deg/s
80 deg/s
1 uV
+
0
100
200
300
ms
B
260
240
220
200
180
N1 latency (ms)
0
20
40
80
Rotation speed (degrees/s)
Mean+/-SE
T5
T6

Switching attention without shifting the spotlight: object-based attentional modulation of brain potentials.

Mitchell Valdes-Sosa, Maria A. Bobes, Valia Rodriguez y Tupac Pinilla

Resumen:

Aún cuando se han reportado evidencias psicofísicas de la atención basada en los objetos, los estudios correspondientes utilizando los potenciales relacionados a eventos (PRE) son escasos. En este trabajo le presentamos a los sujetos escenas visuales que contenían dos objetos superpuestos (superficies transparentes generadas por dos conjuntos de puntos de diferente color que rotaban en sentidos opuestos alrededor de un punto de fijación) o un solo objeto (los mismos conjuntos de puntos manteniéndose estáticos o rotando ambos en el mismo sentido). En cualquiera de los dos conjuntos se producían breves desplazamientos rectilíneos (150 ms) cada ciertos intervalos de tiempo aleatoriamente escogidos entre 350-550 ms. La atención se dirigía sostenidamente a uno de los conjuntos con el objetivo de discriminar la dirección de dichos desplazamientos (eventos). Se compararon entonces los potenciales relacionados con el inicio del movimiento (PR-IM) provocados por los eventos que se produjeron en el conjunto atendido con aquellos provocados por los eventos ocurridos en el conjunto no atendido. Cuando el campo perceptual consistía en dos objetos, se obtuvo una fuerte supresión de los componentes P1 y N1 en los PR-IM asociados con el objeto no atendido. Esta supresión no apareció cuando el campo contenía un solo objeto; aunque encontramos un incremento en la negatividad de selección en los PR-IM asociados al conjunto atendido (seleccionado a partir del color). Como los dos objetos ocupaban la misma región del espacio visual, la supresión P1/N1 no puede ser explicada por la metáfora del foco atencional, sino que es consistente con una selección atencional basada en los objetos operando en estadios tempranos de la visión. Los resultados destacan el papel de la organización perceptual en la habilitación de mecanismos atencionales alternativos.

Switching Attention without Shifting the Spotlight: Object-Based Attentional Modulation of Brain Potentials

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Abstract

■ Although psychophysical evidence for object-based attention has been reported, corresponding studies with event-related potentials (ERPs) are scarce. Here subjects were presented with perceptual fields containing two superimposed objects (transparent surfaces generated by two sets of dots in rigid rotation around fixation, each set of a different color and direction of motion) or only one object (the same dots but either at rest or all rotating in the same direction). Brief (150-msec) rectilinear displacements affected either of the sets at random ISIs of 350 to 550 msec. Attention was directed to one set of dots, guided by color, in order to discriminate the direction of their displacement. Motion-onset ERPs elicited by these displacements were compared for attended and unattended dots. When the perceptual field consisted of two objects, strong suppression of P1 and N1 was obtained in the ERPs associated with the unattended object. No suppression was found with the field containing a single object, although an enhanced selection negativity was found in ERPs associated with attended dots (selected by color). Since the two objects occupied the same region of visual space, the suppression of P1/N1 cannot be explained by the space-based mechanisms but is consistent with object-based attentional selection at early stages of vision. The results highlight the role of perceptual organization in enabling alternative attentional mechanisms. ■

INTRODUCTION

The visual system can be flooded by the information coming from a rich scene. All the input cannot be processed with the same priority. Attentional selection of visual information for further processing could occur on the basis of spatial locations in the scene or alternatively on the basis of higher-level entities such as surfaces or objects. In this article, electrophysiological evidence is presented that reflects the influence of object-based selection on early stages of visual processing, a result similar to that previously found only for spatially based attention.

A substantial body of evidence, coming from psychophysics and neurophysiology, indicates that the brain can choose parcels of information by favoring some regions of visual space over others (Mangun & Hillyard, 1995; Posner & Dehaene, 1994). Spatially based attention is sometimes conceived in terms of the "spotlight" metaphor (Posner, 1980), which in its original formulation allocates processing resources only to information coming from one region of an array representation (each array element coding input from one location) to the exclusion of other areas. The region is usually conceived as a unitary, convex, and compact locus of focused attention (as defined in Yantis, 1992). Related hypotheses posit "gradients" (Downing, 1988) or a "zoom lens" (Eriksen & St. James, 1986), which can be distributed over the array representation. A critical prediction from this family of models is that all signals arising from the attended area are processed to some degree.

Spatially based attention has been supported by cueing experiments, in which advance information about the location of an upcoming stimulus is thought to allow for a correct positioning of the spotlight (Posner, 1980; Posner & Cohen, 1984). Additional support comes from the "flanker" paradigm (Eriksen & Eriksen, 1974), in which spatial proximity increases interference by irrelevant stimuli and also from dual task designs where discrimination accuracy increases if the distance between stimuli for the two tasks is decreased (Hoffman & Nelson, 1981; Sagi & Julesz, 1986). Moreover, an extensive series of studies on visual search (e.g., Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989) provide data consistent with the serial displacement of a small attentional window, when the targets are defined by conjunctions of features (but see Duncan & Humphrey, 1989).

Clear evidence for location-based attention has also been found with event-related potentials (ERPs; Mangun, 1995; Mangun & Hillyard, 1995), the recording of which offers clues on the timing and possible neural basis of the processing operations involved. The earliest work in this direction used sustained-attention designs, in which randomly timed streams of stimuli were flashed to different visual locations (usually opposite hemifields). Attention was directed at one of these locations, while the others were ignored. The basic result has been replicated many times (Eason, Harter, & White, 1969; Eason, 1981; Mangun & Hillyard, 1990; Neville & Lawson, 1987; Van Voorhis & Hillyard, 1977): Stimuli falling within the attended region elicit ERPs that are enhanced in amplitude relative to responses triggered by stimuli placed elsewhere. Notably, P1 (80 to 120 msec) and N1 (160 to 200 msec) amplitudes are modulated by attention, without any change in latency or scalp topography, suggesting a mechanism of gain control of the generators of these components. More recently, similar modifications of either P1 or N1 amplitude have been reported when visual attention has been manipulated in spatial cueing tasks (Eimer, 1993, 1994; Luck et al., 1994; Mangun & Hillyard, 1991) or visual search tasks (Luck, Fan, & Hillyard, 1993), providing a direct link with the psychophysical results mentioned above. The fact that attention modulates exogenous components, with such short latencies, supports the hypothesis that early sensory facilitation is involved (Luck et al., 1994). Also in line with a spatially based spotlight is the finding that when attention must be allocated at two separate locations, responses to irrelevant probes located at an intervening position cannot be suppressed (Heinze et al., 1994).

There is a different electrophysiological outcome when relevant and irrelevant stimuli occur at the same spatial locus (and thus cannot be discriminated by position) and are selected on the basis of simple features. Selection in this case is associated with changes in late, slow, negative components (reviewed in Näätänen, 1992) that have been called *selection negativities* (SNs). Among the stimulus attributes that enable SNs are color (Aine & Harter, 1986; Anllo-Vento & Hillyard, 1996; Harter & Salmon, 1972; Hillyard & Munte, 1984; Wijers, Mulder, Okita, & Mulder 1989) and motion (Anllo-Vento & Hillyard, 1996). Whereas the P1/N1 effects are consistent with the modulation of exogenous components, SNs are endogenous components that appear to reflect additional processing of the selected stimulus. In experiments where attention to space is combined with selection by color or motion (e.g., Anllo-Vento & Hillyard, 1996; Hillyard & Munte, 1984), SN was contingent upon prior selection of location. These findings, together with the short latency of the P1/N1 effect, have been seen as congruent (Hillyard et al., 1996) with models of attention (e.g., Feature Integration Theory; Treisman & Gelade, 1980) that posit a special and early role for space.

However, attentional selection has also been conceived as occurring at levels of representation more elaborate than elementary feature or location maps. Surfaces (Nakayama, He, & Shimojo, 1995), objects (Duncan, 1984), and object-files (Kahneman, Treisman, & Gibbs, 1992) have been proposed as the entities subject to attentional selection. These concepts are related and may be part of a continuum, with visual surfaces at one extreme and completely identified objects that provide access to extra-visual knowledge at the other (He & Nakayama, 1995). We will refer to all these types of attention as object-based although our emphasis is at the lower end of the continuum (prior to object recognition). What is common to all these concepts is the proposal that selection operates only after the visual scene is segmented and perceptual objects are defined: Perceptual organization precedes and conditions attention.

Support for object-based attention comes from studies in which subjects are asked to attend to one of several superimposed objects, where selection based on unsegmented space is difficult if not impossible (Duncan, 1984; Neisser & Becklen, 1975; Rock & Gutman, 1981; Vecera & Farah, 1994). Events (or attributes) in the attended object are detected, discriminated, and remembered better than in the unattended object. Interestingly, two discriminations are performed more efficiently when performed on the same object than when they have to be performed on two different but superimposed objects (Duncan, 1984; Vecera & Farah, 1994).

Additional support comes from studies in which perceptual grouping overrides the role of spatial proximity in several types of task (Driver & Baylis, 1989; Driver, McLeod, & Dienes, 1992; Driver & McLeod, 1992; Duncan, 1995, Kramer & Jacobson, 1991; McLeod, Driver, & Crisp, 1988; McLeod, Driver, Dienes, & Crisp, 1991; Prinzmetal, 1981; Treisman, Kahneman, & Burkell, 1983). Also congruent with object-based attention are findings that surface organization influences different tasks that are thought to depend on attention (Aks & Enns, 1992; He & Nakayama, 1992; He & Nakayama, 1995; Kleffner & Ramachandran, 1992; Nakayama et al., 1995). The latter set of results has led Nakayama et al. (1995) to suggest that attention and other higher visual processes must operate on intermediate surface-level representations.

While a growing body of evidence offers psychophysical support for object-based attention under certain circumstances, corresponding ERP studies are scarce. Is object-based attention reflected by the gating of exogenous components or the modulation of endogenous components? In this article we search for neurophysiological evidence of object-based attention by combining several of the strategies outlined above. In our experiments, objects were defined by two sets of dots that differed in color although they were spatially interspersed. The critical variable in the experiments was perceptual organization (Bruce & Green, 1990), induced by what we call the baseline visual scene (Figure 1A, B, and C). The baseline could compel the subject to see two objects or a single object in the stimulus displays. These different perceptual fields were expected to influence the choice of attentional strategies.

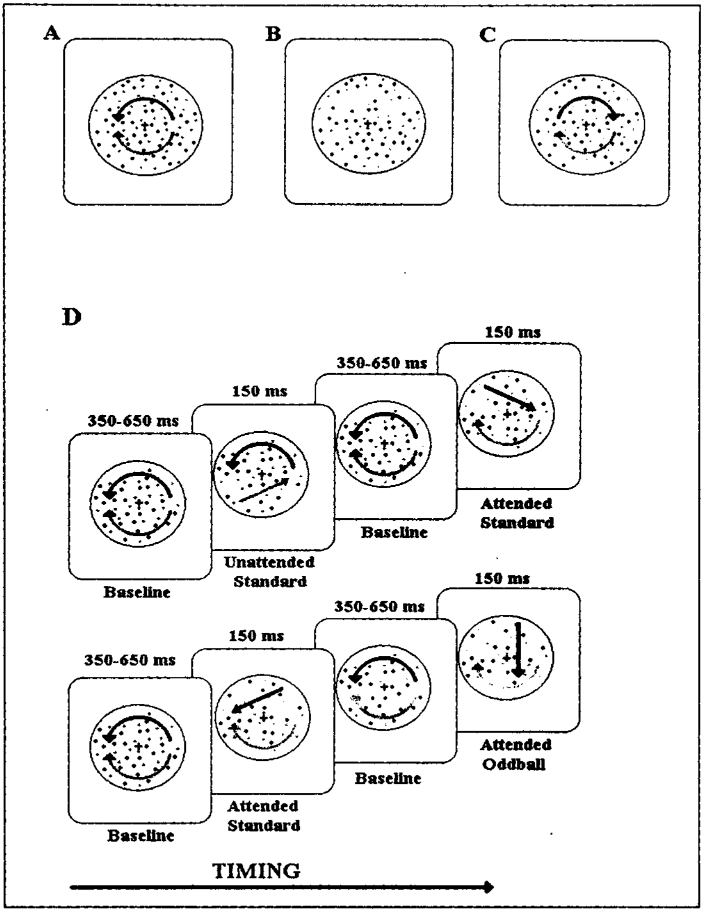


Figure 1. Representation of the stimulus material. (A) Two-object rotatory baseline perceptual field, in which two clouds of dots rotated in opposite sense (represented as gray and black on white, although in the experiments 100 red and 100 green dots on a black background were used). This generated the percept of two transparent surfaces sliding across each other. (B) One-object stationary perceptual field. All dots were motionless during the baseline perceptual field, which was seen as one object. (C) One-object rotatory perceptual field. All dots rotated in the same direction, which was seen as only one object. (D) Example sequence of events for experiments using two-object rotatory perceptual fields. Blocks began with the baseline perceptual field. At random intervals, the dots of one color were linearly and simultaneously displaced, while the other set continued to rotate. The number of translated dots moving in the same direction (i.e., coherently) varied across experiments. In this example, motions of the gray dots were unattended, whereas events for black dots were attended (and the direction of translations discriminated). Eighty percent of the translations were in the oblique directions and were the standards, and the other 20% were translations in the cardinal directions and were the oddballs (the infrequent targets to be responded to). ERPs were recorded in synchrony with the onset of the translations, separately for attended standards, attended oddballs, unattended standards, and unattended oddballs (the last not shown in the example).

In the baseline scene leading to the perception of two objects, the dots within each set presented a common rigid rotational motion, but the differently colored swarms moved in an opposite sense. These superimposed objects formed transparent surfaces (Andersen, 1989; Andersen & Wuestefeld, 1993; Qian, Andersen, & Adelson, 1994; Stoner, Albright, & Ramachandran, 1990). In the scenes perceived as containing one object, all the dots were motionless or all the dots rigidly rotated in the same direction. In all cases (two or single object scenes), the subjects were required to attend to brief linear displacements of one set of dots while ignoring such events in the other set. These translations were only partially coherent, that is, only a subset of dots moved in the same direction, and the subjects were asked to discriminate the dominant direction of motion (Figure 1D).

In other words, in the first situation the subjects had to attend to displacements within one of two preexisting objects (segregated by motion and color), whereas in the second situation attention was directed to the similar displacements imposed on part of a single object (segregated from the whole by color). It is important to note that in all the experiments both attended and unattended stimuli originated from the same region of visual space, thus thwarting selection exclusively based on location.

The motion-onset ERPs (MO-ERPs) elicited by the brief linear movements of either the attended or unattended sets of dots object were then compared. This was a departure from previous ERP studies of attention that have used flashed stimuli. Motion modifies objects without destroying their identity (Kahneman et al., 1992). Moreover, motion onset elicits a P1/N1 complex that has been described by several groups (Bach & Ullrich, 1994; Göpfert, Muller, & Simon, 1990; Kuba & Kubová, 1992a and 1992b; Schlykowa, van Dijk, & Ehrenstein, 1993). Results from a previous study had suggested that MO-ERPs are sensitive to attentional effort in motion-coherence discrimination tasks (Valdes-Sosa et al., 1994). It was expected that if object-based selection occurred at early stages of vision, the P1 and N1 components of the MO-ERP would be modulated by attention.

RESULTS

Experiment 1

In this experiment, the effects of attention on the MO-ERPs obtained with two types of perceptual field (two objects or a stationary single object) were compared. A between-subject design was employed. Because no significant effects related to the color of the dots were found either in the MO-ERP waveform or in the task performance, this factor is ignored in the description of the results from this and the next experiment.

All the subjects in the group presented with the two-object baseline scene reported perceiving two transparent surfaces sliding across each other. Figure 2A depicts the MO-ERP waveforms elicited by attended and unattended standards (translational motion in the oblique direction). In responses for attended stimuli, clear ERP components were observed, whereas a very strong suppression was found of all the components in the MO-ERPs related to the unattended stimuli. Similar early components and attentional effects were also found for MO-ERPs elicited by targets (see Figure 3). The latencies of the principal MO-ERP components from this and the next group are displayed in Table 1.

In a repeated-measures analysis of variance (rm-ANOVA; including both standards and targets), on data from the posterior sites, the suppression of responses elicited by unattended stimuli was reflected by highly significant effects of attention on P1 amplitude ($F(1, 7) = 28.0, p < 0.0011$) and on N1 amplitude ($F(1, 7) = 19.98, p < 0.0029$). No statistically significant effects of attention were found for P2 or later components, despite the striking variations observed in the grand average MO-ERPs. Examination of the individual MO-ERPs revealed that two of the eight subjects presented a deviant pattern of components, with large negative peaks in the 270 to 350-msec range that generated a large variance for mean amplitude measures on this component.

The N2 did not differ between responses following attended standards and targets (see Figure 3) at Pz. However, at posterior sites the N2 was larger for targets than for standards (not shown in figures), an effect that was significant in a rm-ANOVA ($F(1, 7) = 10.63, p < 0.014$). At the parietal sites, an enlarged late positive component (LPC) component was present for targets but only when attended (see Figure 3). This effect on LPC amplitude at Pz was highly significant ($F(1, 7) = 22.3, p < 0.0022$). The equivalent comparisons for unattended stimuli were nonsignificant.

In the group of subjects presented with the single-object stationary scene (which corresponded to the percept of one bicolored object), large MO-ERPs were elicited by both attended and unattended stimuli, and no effects of attention or stimulus type (standard vs. target) were evident on the early P1 and N1 components (see Figures 2B and 3). P1 and N1 in this group were slightly larger than in the first group (about 1.5 μV; a difference, however, only marginally significant in the between-group comparison for the attended trials, $F(1, 14) = 3.72, p < 0.074$). The latencies of the peaks were also somewhat shorter (about 35 msec). These results in conjunction with those of the previous group suggested the presence of moderate masking of the stimulus events by the baseline rotational motion.

The earliest effect of attention began at about 234 msec and consisted of an enhanced negative wave (SN) that overlapped the late part of N1, P2, and N2 as defined for the MO-ERPs associated with unattended events. This enhanced negativity was very widespread over the scalp and was reflected by a significant effect of attention on the time window for N2, as revealed by an rm-ANOVA ($F(1, 7) = 14{,}41, p < 0.01$) for the posterior sites. The amplitude of this component did not differ between targets and standards. In the MO-ERPs associated with attended targets, the LPC at Pz was enhanced with respect to attended standards ($F(1, 7) = 26.5, p < 0.0013$). This effect was absent in the unattended stimuli (see Figure 3).

Experiment 2

To assess the replicability of Experiment 1 and to introduce additional controls, the effects of attention on MO-ERPs were examined in a within-subject design for three conditions, each presented in a different block of trials. The two-object perceptual field was used twice, once as in Experiment 1 (with 60% coherence of motion for stimulus events) and in another condition with 100%

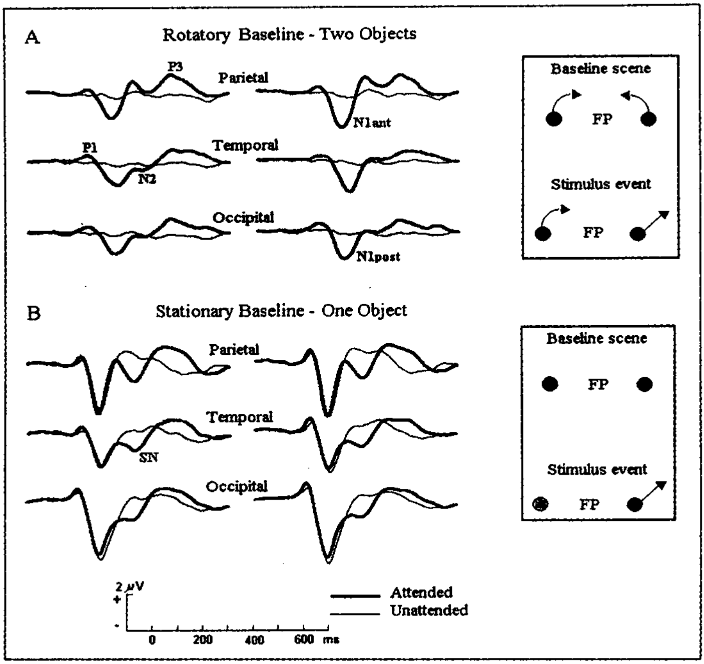


Figure 2. Grand average MO-ERPs from Experiment 1. Responses associated with attended and unattended standards are shown, comparing the amount of attentional suppression when two objects were present (A) and when only one (static) object was present (B). Responses from attended and unattended events are overlaid (and collapsed over color). The column on the left represents waveforms from sites on the left side of the scalp (P3, T5, and O1), and the column on the right from the right side (P4, T6, and O2). Note that positive deflections point up. On the right of the waveforms, the behavior of one element from each of the sets of dots is represented during the baseline scene and during the stimulus event. Note the large suppression of responses (P1 and N1 in particular) in (A), whereas no suppression can be observed in (B). The selection negativity (SN) is indicated in (B). The same conventions are maintained in Figure 4.

coherence in the stimulus motion. A condition with a single rotatory object (all dots moved together) was also used.

The MO-ERPs elicited by standards in the block with a perceptual field containing two objects (60% coherence) are presented in Figure 4A. Due to the smaller number of events averaged and the smaller number of subjects, there was more MO-ERP variability (specially for slow activity) in this experiment than in the previous one, which affected P1 measures most. This was compensated for, in the grand average plot and for the P1 measurements in individual MO-ERPs, by digitally high-pass filtering at 2.0 Hz (third-order Butterworth filter). The waveforms for attended stimuli were similar to those obtained for Group 1 in the two-object baseline, with comparable latency values. A large suppression of all MO-ERP components was associated with the unattended stimuli. The effects of attention on P1 ($F(1, 5) = 17.23, p < 0.0089$) and N1 ($F(1, 5) = 14.39, p < 0.013$) amplitudes were significant.

In the other block, all the dots rotated in the same direction during the baseline scene and only one object was perceived. This block served to determine if the MO-ERP differences between Groups 1 and 2 were due only to the presence or absence of motion in the baseline scene. The MO-ERPs for this condition are displayed in Figure 4B. A very small effect of attention was observed on P1, which was only marginally significant ($F(1, 5) = 5.86, p < 0.06$) in the rm-ANOVA. Also, a small effect of attention on N1 amplitude was observed, which was not significant ($F(1, 5) = 4.8, p < 0.08$). However, a enhanced negativity (SN), beginning at about 170 msec and lasting up to about 378 msec (that overlapped the late N1, P2, and N2 time windows), was present at the posterior sites for attended stimuli. The MO-ERPs in the N2 time window were significantly more negative for attended stimuli ($F(1, 5) = 15.04, p < 0.012$).

The last block also corresponded to a baseline scene with two rotating objects but with 100% coherent stimulus motion. Discriminating the direction of motion for these stimuli was much easier than for the partially coherent stimuli (see below). This control was introduced to establish if the diverging electrophysiological signatures found for the baseline scene with two objects

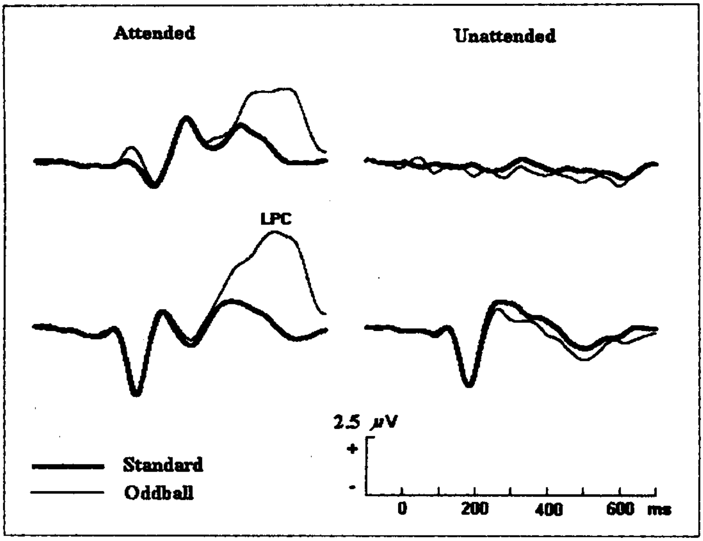


Figure 3. Grand average MO-ERPs at Pz from Experiment 1. Responses to standards and oddballs are compared. On the right are the ERPs elicited by attended stimuli, and on the left are ERPs elicited by unattended stimuli. The first row depicts responses from the two-object group, and the second row responses from the one-object group. Note the large LPC associated with attended targets in both groups. No modulation of LPC was found for unattended stimuli.

and the baseline with one object was due to the difficulty of the task. Despite the ease of the task when motion was completely coherent, a large suppression of P1 and N1 was observed for this condition (waveforms are not shown but are very similar to those in Figures 2A and 4A; see also Figure 5). The effects of attention on P1 ($F(1, 5) = 14.09, p < 0.013$) and N1 ($F(1, 5) = 6.85$, $p < 0.047$) amplitudes were significant.

For all three blocks, the LPC elicited by attended targets were larger than those elicited by attended standards. All these effects on LPC were highly significant and strongest at parietal sites (all $p < 0.001$). In responses related to unattended stimuli, no differences were found between standards and targets. These effects (not shown) were similar to those depicted in Figure 3.

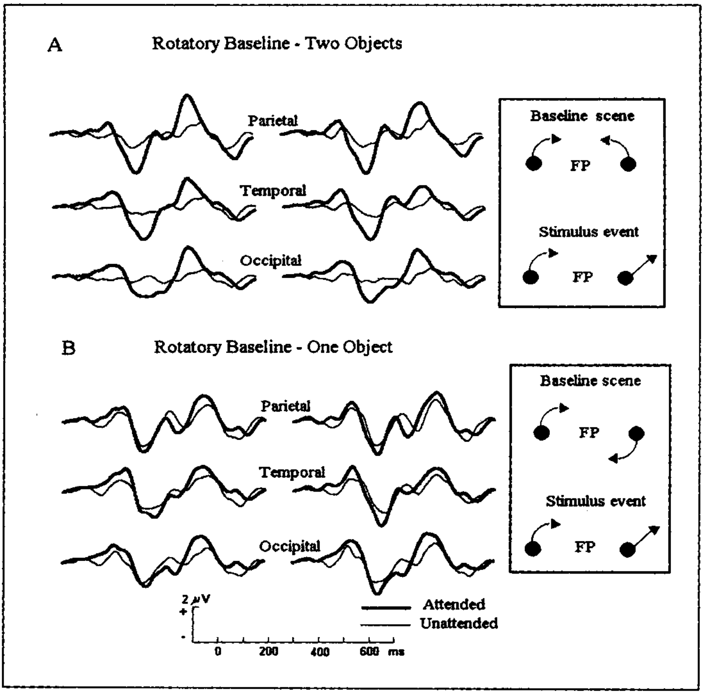
Comparison of P1/N1 Amplitude Across Experiments

Group means of the P1 to N1 amplitude (obtained by subtraction of the same amplitude measures used in the ANOVAs and averaged across the posterior sites: T5, T6,

Table 1. Latencies (in msec) of the MO-ERP from the two groups in Experiment 1. Each group had eight participants.

Component	*P1*	*N1ant*	*N1post*	*P2*	*LPC*
			ERPs elicited with two-object baseline		
Mean	161	229	269	328	562
SD	24	20	14	40	56
Range	134-203	219-240	244-293	304-400	484-628
			ERPs elicited with one stationary object in the baseline		
Mean	110	179	200	263	561
SD	21	17	36	31	59
Range	84-153	166-186	166-281	206-308	500-685

Figure 4. Grand average MO-ERPs from Experiment 2. Only responses associated with standards are shown. A within-subject design was used. (A) ERPs for the condition with a baseline scene comprising a two-object rotatory scene. Note the large suppression of P1 and N1 responses to unattended stimuli, which replicates Figure 2A. Similar results are obtained for the same subjects (not shown) when the translation motion was 100% coherent. (B) ERPs for the condition with a baseline scene comprising a one-object stationary scene. Only moderate suppression of P1 and N1 is present for unattended stimuli.



O1, and O2) are displayed in Figure 5, which serves to summarize the MO-ERP data. P1-N1 amplitude was severely suppressed for unattended stimuli whenever the baseline scene consisted of two rotating objects (a reduction of about 86 to 94%). When the baseline scene consisted of only one object, this early attentional suppression was absent (as in the case of a static object) or moderate (as in the case of one rotating object, where the decrease was about 39%). Clear signs of attentional selection based exclusively on color are present only in later portions of the MO-ERP in the form of an SN.

Behavioral Results

Accuracy was measured by the Levenshtein Distance (LD, see "Methods"). If the subjects were completely accurate in reporting the direction in which all targets moved (100% correct identification), the LD was zero; if they were failed completely, the LD was equal to 100. Figure 6A displays the group mean for all the conditions (collapsed over the color of the dots because this factor has no influence on LD). The accuracy in all conditions with rotating perceptual fields was similar and larger than for other conditions, consistent with a masking effect of the baseline motion on the stimulus motion. For the two-object baseline field with completely (100%) coherent stimulus motion, the rate of mistakes was low, as reflected by small LD values. Since suppression of P1/N1 was obtained for this condition, as for all two-object baseline fields, the suppression can be dissociated from the difficulty of the task by itself.

In a between-subject ANOVA for the results of the two groups in Experiment 1, significantly more mistakes were found for the rotating dots than for the static dots conditions ($F(1,28) = 41.4, p < 0.001$). In Experiment 2, the accuracy from both conditions with 60% stimulus-motion coherence (two- and one-object perceptual fields) did not differ from each other. However, fewer mistakes were made in the coherent-stimulus condition than in the other two conditions (for both comparisons: Wilcoxon, $z(6) = 2{,}21, p < 0.028$).

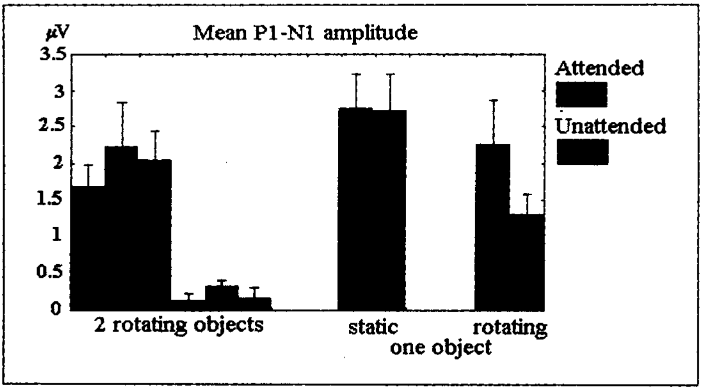


Figure 5. Mean P1 to N1 amplitudes as a function of the baseline scene and attention. The first group of bars correspond to the three conditions in which the two-object baseline scene was used (from left to right for each attentional state: data from Experiment 1, then the 60% coherence condition in Experiment 2, and last the 100% coherence condition in Experiment 2). Note the large P1-N1 suppression for unattended stimuli with the two-object baseline scene. In the two conditions where a one-object scene was used little suppression was found (static condition for Experiment 1 and rotatory condition for Experiment 2). The whiskers correspond to standard errors.

DISCUSSION

The most important finding in this study was a very strong suppression of the motion-onset P1 and N1 associated with unattended stimuli (despite their spatial superposition with the attended stimuli) in all conditions with two objects in the baseline perceptual field. When the same elementary features were integrated into a single object during baseline (by either putting all dots at rest or by having them move together), only moderate or no suppression of responses to unattended events was found. Thus, attentional suppression of P1/N1, when attended and unattended stimuli arise within the same area of visual space, seems to require that the two types of stimuli be related to distinct objects.

The suppression was not related to task difficulty per se, because it was found in the difficult two-object task with partially coherent stimuli (Experiments 1 and 2) as well as in the very easy two-object task (Experiment 2) with completely coherent stimuli. Although some amount of forward masking was produced by the baseline motion on the stimuli, as evinced by the ERP and performance data, masking effects cannot explain the differences in responses to attended and unattended stimuli. Nor can masking explain the fact that both attended and unattended stimuli elicited large MO-ERPs when only one rotating object was present during baseline.

In order to compare the results from this article and other ERP studies of attention, it is important to remember that MO-ERPs and ERPs elicited by luminance increments and pattern onsets may not have entirely the same generating sources (Kubová, Kuba, Spekreijse, & Blakemore 1995; Schlykowa et al., 1993). Moreover, the few studies on attention using moving stimuli (Anllo-Vento & Hillyard, 1996; Neville & Lawson, 1987) may not be strictly comparable due to the short stimulus onset asynchronies (SOAs) employed between pattern and motion onset. Pattern onset severely masks the MO-ERP at SOAs lower than 400 msec (Valdes-Sosa, Bobes, & Torriente, submitted). In this article the motion of visual elements that were continuously present was used to avoid masking by pattern onset.

Despite the difference in stimuli, the data from this study replicates previous findings in three aspects. First, the modulation of P1 and N1 by attention seems to involve the gain control of exogenous components, as described for experiments with location-based attention using flashed (Eason, 1981; Eason et al., 1969; Mangun & Hillyard, 1990; Van Voorhis & Hillyard, 1977) or moving stimuli (Anllo-Vento & Hillyard, 1996; Neville & Lawson, 1987; Valdes-Sosa et al., submitted). Second, P1 and N1 are not affected by selection on the basis of color when positional cues are absent. Instead, attended stimuli are associated with a SN (Aine & Harter, 1986; Anllo-Vento & Hillyard, 1996; Harter & Salmon, 1972; Hillyard & Munte, 1984; Näätänen, 1992; Wijers et al., 1989). This is the result we found for the MO-ERP when one object (stationary or rotating) was present in the baseline scene, and the attended dots were selected only by color. Finally, the late positive complex (LPC, represented by positive peaks in the 400 to 500 msec range) in all our experiments was enhanced in the trials associated with attended target stimuli, relative to trials associated with attended standards. This pattern was absent for the unattended trials. The hierarchical dependence of the ERP signs of target detection on previous attentional engagement has been repeatedly reported (reviewed in Näätänen, 1992, and Hillyard et al., 1996).

Nevertheless, the attentional modulation of ERP wave-

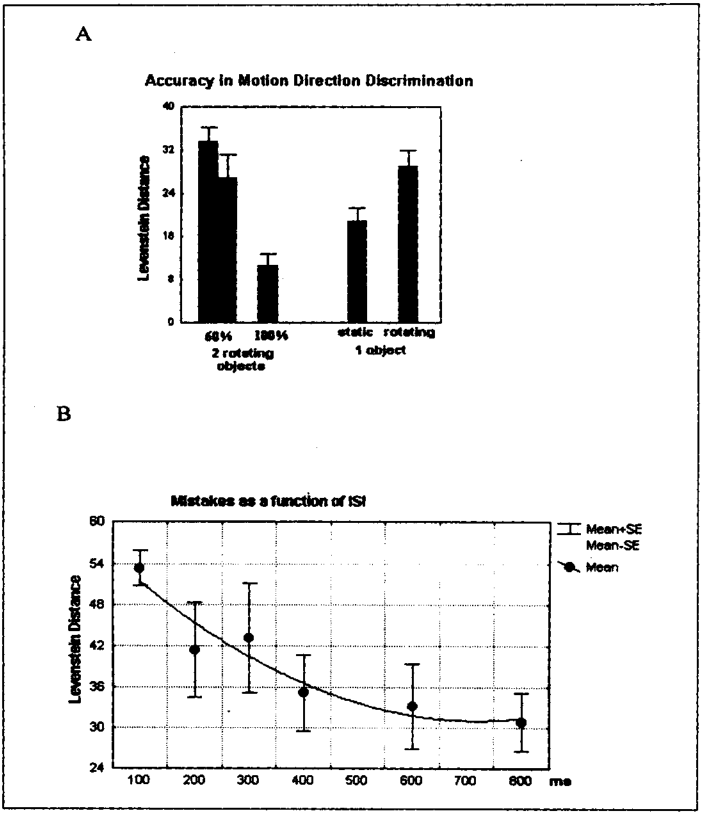


Figure 6. (A) Levenshtein distance as a function of the baseline perceptual field. From left to right, there are two replicates obtained with the two object field and 60% coherence stimulus motion, from Experiment 1 (left) and Experiment 2 (right); then results with 100% coherent stimulus motion from Experiment 2 are shown (note low error rate); finally the static one-object field used in Experiment 1 and the rotating one-object field used in Experiment 2 are shown. (B) Levenshtein distance as the function of ISI. Mean and standard error of the accuracy of six subjects in a task with two rotating objects in the baseline as a function of ISI duration (all other parameters as in the ERP experiment except that the ISI was held constant within blocks). The fitted curve is a second-order power function.

forms found in previous experiments (Eason, 1981; Mangun & Hillyard, 1990; Van Voorhis & Hillyard, 1977) are not as large as the virtually complete suppression of unattended stimuli described in this article. This discrepancy could be related to a possible difference in stimulus salience in the two types of study. Evidence consistent with different roles for luminance increments and motion in attention was reported by Nothdurft and Parlitz (1993). They found that express saccades were generated only toward luminance-defined targets and not toward motion- or texture-defined targets. Also, several visual search studies (Yantis & Hillstrom, 1994; Yantis & Jonides, 1990) have demonstrated the unique role of abrupt luminance increments in automatic attentional capture. Whereas abrupt luminance increments usually capture attention, motion seems to do so only when it segregates an element from a perceptual group and creates a new object (Hillstrom & Yantis, 1994; Yantis, 1993).

With our two-object baseline scenes, the stimulus events probably did not disrupt scene organization. To phrase it in the terms used by Kahneman et al., (1992), stimulus motion did not create a new object; it only changed the contents of an existing "object-file." Thus, according to Yantis (1993), these movements should not capture attention automatically, and strong suppression of unattended signals would be possible. Experiments in which only one object was present in the baseline scene provide the converse situation. Perhaps the abrupt luminance changes used in previous ERP experiments were more salient and tended to capture attention automatically. Therefore, strong suppression of signals that should be ignored would have been more difficult to obtain in those experiments.

However, the difference with previous studies runs deeper. Previous ERP studies of location-based attention are compatible with the metaphor of a spotlight selecting compact regions of external space. According to this metaphor, selection of all stimuli falling within the attended set of locations is compulsory to some degree. It is not possible to suppress early ERP components elicited by unattended stimuli that are near or at the same position as relevant stimuli when the stimuli are defined by pattern onset and/or luminance increments (Mangun & Hillyard, 1990; Heinze, Mangun, & Hillyard, 1990). In one study (Heinze et al., 1994), if attention was directed to the extremes of a horizontal symbol array, probes to intermediate (supposedly unattended) positions also elicited an enhanced P1. This is consistent with the idea that the attentional focus must be unitary and cannot be split in noncontiguous zones. In contrast, we found suppression of unattended stimuli originating in the same region of visual space as attended stimuli.

Could the subjects in this study have been tracking the individual elements, thus effectively partitioning the stimulus region into attended and unattended subregions (a "microspotlight" account)? This seems unlikely because in the two-object condition the dots from both surfaces were highly interspersed, rapidly changed positions, and the elements from different objects crossed over each other frequently. Moreover, Pylyshin and Storm (1988) have found that it is possible to follow accurately only up to about five moving targets, a set size much smaller than the hundred dots used for each surface in our study. Also, because the stimulus motion was only partially coherent in most conditions, following individual dots would have been highly misleading. On debriefing, many of the subjects said that they could only solve the direction discrimination task by disengaging from individual dots and trying to detect the global sense of motion (as originally described by Williams & Sekuler, 1984). Furthermore a microspotlight account would predict attentional effects on P1/N1 in the dots-stationary and single-object conditions, which did not occur.

The fact that in this study attention-suppressed responses to stimuli spatially interspersed with attended stimuli is incompatible with the family of models that Nakayama and He (1995) call *Cartesian*, where the attentional focus is specified in terms of coordinates in a viewer-centered geometric feature space or as locations in an array representation (see also Yantis, 1992, and Vecera & Farah, 1994). This finding is also incompatible with modified spatial models of attention such as modified feature integration theory (Treisman, 1988; Treisman & Sato, 1990) or the related guided search model (Wolfe et al., 1989), in which goal-directed activity operates on an element-by-element basis, thus capturing with difficulty the effects of motion phase (Duncan, 1995). In this study suppression of P1/N1 was found only when the two sets of dots were not moving in phase. It is not clear how modified spatial selection theories could explain this finding.

The most parsimonious explanation of P1/N1 suppression in our experiments is the early selection of some intermediate representation (beyond elementary feature maps), where perceptual linkage leads to the acceptance or rejection of whole groups of elements (Duncan, 1995; Duncan & Humphreys, 1989, 1992). This representation could correspond to an interpolated surface, as posited for the derivation of structure-from-motion (Hildreth, Ando, Andersen, & Treue, 1995; Treue, Andersen, Ando, & Hildreth, 1995).

The previously reported lack of suppression for ERPs elicited by unselected stimuli placed at, or near, attended locations (see above) is not irreconcilable with the findings from this study. As discussed above, sudden-onset stimuli tend to capture attention automatically. This may explain why it seems unavoidable to attend all events within a selected region of space in some conditions. The Kramer and Hahn (1995) study supports this interpretation. The matching of two characters is affected by distracters, placed between the targets, if all the stimuli are presented suddenly. With non-onset stimuli, created by eliminating segments of a premask, or placeholder, subjects are able to ignore the distracters.

The results presented in this article, together with those from psychophysical studies (Driver, McLeod, & Dienes, 1992; Duncan, 1984; He & Nakayama, 1992; McLeod et al., 1988; McLeod, Driver, Dienes, & Crisp, 1991; Vecera & Farah, 1994), provide converging evidence for object-based attention. If there is an attentional spotlight, it shines on an internal representation and not on a region of the visual field.[1] Spatial and object-based attentional mechanisms are not mutually exclusive (Duncan, 1984) and could be optimal for different computations (Vecera and Farah, 1994). The conditions employed in this study were designed to favor object-based attention, conditions that were absent from previous ERP experiments. The results highlight the role that perceptual organization could play in enabling one attentional mechanism or the other.

Interestingly, the same early electrophysiological signature previously found to reflect spatial attention (P1/N1 modulation) can also be associated with object selection. The modulation of P1 in this study began as early as 100 msec after the stimulus onset. The implications of this finding are worth examining. Visual perception is frequently conceived as the sequential construction of distinct scene representations, moving toward an increasing degree of abstraction. As stated by Verghese and Stone (1996), "it is generally assumed that the segmentation and grouping of pieces of the image into discrete entities is due to 'later' processing stages, after the 'early' processing of the visual image by local mechanisms selective for attributes such as color, orientation, depth, and motion." For example, in one influential theory (Marr, 1982) an early primal sketch (built with elements similar to the low-level receptive fields traditionally assigned to the striate cortex) is followed by the 2½-D map (where surfaces are first explicitly represented), which is then succeeded by an object-centered 3-D representation obtained after recognition processes (the first two stages were considered to be viewer centered). Vecera and Farah (1994) consider space-based attentional mechanisms to be tied to early array-based representations (such as the primal sketch) and object-based attentional mechanisms to be tied to 3-D representations. This could be seen as implying a later timing for object-based attention as compared with spatially based attention.

The fact that both space- and object-based attention modulate similar early ERP components strongly suggests that, instead of acting at successive stages of perception, they can correspond to alternative computations on the same representations. In other words, selection by location and selection by motion-defined objects could use the same early attentional mechanisms. This raises questions about how special or unique is the role that space plays in attention. The ERP evidence is congruent with increasing evidence that surface and object properties, determined by interactions extending beyond the classical receptive fields, are reflected at the earliest visual cortical stages (Verghese & Stone, 1996), including V4 (Schein & Desimone, 1990), MT (Allman, Miezin, & McGuinness, 1985), V2 (Peterhans & von der Heydt, 1989), and even V1 (Knierim & Van Essen, 1992; Lamme, 1995; Rossi, Rittenhouse, & Paradiso, 1996; Singer, 1993). The same neurons that code for local contour, motion, and other properties may contribute to the construction of extended surface and object representations (Nakayama et al., 1995).

The motion-onset response has not been used much in cognitive psychophysiology. The very large effects of attention found here for this ERP, and its usefulness in attesting object-based attention, suggest that it should be employed in further studies of visual cognition.

METHOD

Subjects

Two groups of eight individuals participated in the first experiment, and one group of 6 individuals participated in the second experiment. Since the motion discrimination task used in the study was difficult, potential subjects were first screened by running several blocks and were replaced if practice did not lead to accurate performance (which happened in about 20% of the cases). All the subjects had normal or corrected-to-normal vision and no history of neurological disorders. Also, all were university graduates, with experience in similar psychophysical experiments. Ages ranged between 24 and 45 years (with a median of 29). One subject in the first group and one in the third were female.

Stimulus Material

Visual stimuli were presented on a sVGA monitor (frame rate 60 Hz, noninterlaced) placed 50 cm from the subjects and controlled by a 66-mHz 486 microcomputer. The background was black. A small white circle of about 28 arcmin in diameter was placed at the center of the screen as fixation point. The stimuli consisted of two superimposed sets of 100 dots each, one set red and the other green. Each dot was 1 pixel in diameter (about 4.6 arcmin). Red was achieved at each dot by turning off the G and B guns of the CRT and placing the R gun at it maximum level. Heterochromatic flicker photometry was then employed for each subject to obtain green dots that were equiluminant with the red by adjusting the G gun (R and B off). Dots were painted in randomly selected locations within an imaginary circle with a diameter of about 6.9° and centered on the fixation point. The average dot density was about $5.4^{\circ 2}$. The different types of apparent motion used in the experiments were achieved by continuous redefinition of the position of the dots, in synchrony with the video signal.

Baseline visual scenes were presented at the beginning of each block of trials and were only substituted during the brief stimulus events. Three baseline scenes were used (Figure 1A through C). In the first baseline, the red dots rotated rigidly around the fixation point in clockwise direction, whereas the green dots rotated counter-clockwise. The speed of rotation was 3.3°/sec. This baseline was perceived as two semitransparent surfaces moving in the same area of visual space. In the second baseline, the dots were stationary and were perceived as one multicolored object. In the third baseline, both green and red dots rotated in clockwise direction at 3.3°/sec. This baseline was perceived as one rotating object. Since fixation at the center was required, it was very difficult to pursue the dots visually during the rotational baselines.

Stimulus events consisted of brief (150 msec) linear displacements of one of the sets of dots (dots of the other color continued as in the baseline), which were the object of a direction discrimination task. Only displacements in the cardinal and diagonal directions were selected (possible directions varied in steps of 45°). Except for one control condition, the displacements were partially coherent, with 60 of the dots moving in the same direction and the other 40 moving in one of the seven other possible directions, randomly selected for each of these dots. Partially coherent stimuli were employed to induce attention to the complete ensemble, instead of a focus on individual dots. Linear displacements were at a speed of about 4°/sec. If a dot passed the border of the imaginary circle surrounding the baseline, it was wrapped around to an opposite but symmetrical position on the circle. After the stimulus event, dots returned to their baseline state.

Interstimulus intervals (ISIs) were obtained from a uniform distribution ranging from 350 to 650 msec (SOAs of 500 to 800 msec). The direction of each stimulus event and the set of dots involved were randomly selected for each event. Displacements took place in the oblique directions on 80% of the stimulus trials and were designated as standards. Displacements in the cardinal directions took place on 20% of the stimulus events and were designated as targets (see Figure 1D).

Procedure

Experiments took place in a room with dim illumination while the subjects sat in a comfortable chair with a headrest. After fixating the center circle, each block was initiated by the subjects pressing the space bar of the computer keyboard. The subjects were instructed to maintain fixation and minimize body movements and eyeblinks during recording blocks.

The task was to attend to the dots of one color, while ignoring the dots of the other color. The subjects were asked to withhold responses to the standards and to indicate the direction of coherent motion of the attended targets (motion in the cardinal directions) on the arrow keys of the computer keyboard. Accuracy was emphasized over speed, and the system used for scoring did not depend on the timing of the response. The stimuli were presented in runs of 100 to 200 events, lasting from about 1.5 to 2.5 min. Several runs comprised a block. After each run, visual feedback on the accuracy of performance in the target direction discrimination task was provided. Subjects rested between runs and blocks for several minutes.

The discrimination of the attended stimuli was gauged by the subjects' ability to report the direction of target motions as each occurred. For this the Levenshtein distance or edit distance (Kohonen, 1989) was applied to each run. The Levenshtein distance is the most commonly used dissimilarity measure between linear strings of discrete symbols. If A represents the string of correct responses to a sequence of stimuli, and B is the string of actual responses made by the subject, the Levenshtein distance L(A,B) reflects the three kinds of errors that may occur in B: replacement of a correct response by a wrong one, deletion of a correct response (i.e., omission error), and insertion of a response (commission error). More precisely, this distance L(A,B) is equal to the minimum number of errors (replacements plus deletions plus insertions) that allow one to generate the response string A from B.

In our case, one sequence was an ordered list of symbols representing moves made in the cardinal directions for the attended dots. The other sequence was the list of symbols representing responses made by the subject. The distances were rescaled to values from 0 to 100.

A pilot study to determine the optimal ISI was carried out with six subjects (not participating in the ERP study). The baseline with two objects was presented, and a fixed ISI was used in different runs of 100 trials. The Levenshtein distance decreased as a function of ISI length (i.e., with longer ISI the sequence of target directions was reproduced more exactly). The largest values corresponded to an ISI of 100 msec (the smallest ISI used) and the curve leveled off at about 550 to 660 msec. The range of ISI chosen for the ERP studies straddled this time window in order to impose a large perceptual load without too much loss of accuracy (see Figure 6B).

Design

In the first experiment, two groups of eight subjects attended to the green dots in one block and red dots in another. The order of the blocks was counterbalanced over subjects. Five runs of 200 stimulus events were presented in each block. One group was presented with the baseline scene comprised of two objects. The other group was presented with the stationary baseline scene using an analogous design to the first experiment. In the second experiment, six subjects were presented with three different baseline scenes: the two-object scene (a replication of the first experiment), a control condition in which the stimulus displacements were 100% coherent, and the baseline scene in which all dots rotated in the same direction. Half of the subjects attended the green dots and half the red dots. Four runs of 150 stimulus events were presented in each condition.

Electrophysiology

Electrophysiological data acquisition and analysis were carried out on a MEDICID 3E system. Disk electrodes (Ag/AgC1) were placed with electrolytic paste on eight active derivations (Pz, Oz, P3, P4, T5, T6, O1, and O2) of the 10/20 international system. All active electrodes were referred to linked earlobes. Interelectrode impedance was always kept below 5 kΩ. Bipolar derivations were used to record the electroculogram (EOG), with electrodes just lateral to the external canthi for the horizontal movements and 1 cm above and below the left eye for the vertical movements. The signals were filtered between 0.5 and 70 Hz (3 dB down). Additionally, a notch filter with a peak at the power line frequency was used. In each trial, marks corresponding to stimulus events (linear motion onset) were co-registered with the amplified and digitized electroencephalogram (EEG) (12-bit resolution), which was sampled at a rate of 250 Hz and stored on magnetic disk for off-line analysis.

The continuous EEG record was windowed with a prestimulus baseline of 100 msec before pattern onset, and a 700-msec poststimulus epoch. Each EEG segment was visually inspected and trials with artifacts or excessive activity in the EOG were rejected. This eliminated about 5 to 25% of all stimulus events, which in Experiment 1 resulted in individual standard ERPs based on the average of about 600 to 760 events (collapsed over color) and individual oddball ERPs based on about 150 to 190 events. The corresponding averages in Experiment 2 were based on about 180 to 228 events and 45 to 57 events, respectively. For every subject, averaged ERPs synchronized with motion onset were obtained for all recording sites, for each stimulus condition.

The average amplitude of the ERP waveforms was measured for five different components: P1, N1 (posterior), N2 (at T5, T6, O1, and O2 sites), P2, and a late positive complex (LPC, at P3, P4, and Pz). The anterior N1 was not analyzed. These components were measured for each individual, in time windows centered on each peak and defined separately for ERPs associated with the static baseline scene (the following are in msec, P1: 90-120; N1: 160-240; P2: 220-290; N2: 300-360; LPC: 500-640) and the ERPs associated with rotating baseline scenes (the following are in msec, P1: 115-180; N1: 215-290; P2: 280-340; N2: 330-400; LPC: 500-640). All data points were corrected (prior to plotting or measurement) by subtracting the average prestimulus amplitude value. Grand average ERPs were calculated for all groups of subjects for each site and condition. Separate rm-ANOVAs were performed in each group (or condition of Group 3) with Attention, Stimulus type (Target or Oddball), Color (of the dots), and Site as main effects for each component with data from the respective sites defined above. The Greenhouse-Geisser procedure was used, when appropriate, to mitigate violations of the sphericity assumption in repeated-measures designs (Jennings & Wood, 1976).

Note

1. We thank a reviewer for pointing out this analogy.

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Dependence of attentional shift times on local scene organization

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Resumen:

Al procesar una escena natural es necesario reposicionar la atención entre los objetos que la componen. Las mediciones de la duración de estos cambios atencionales discrepan entre sí, siendo la base de diferentes teorías (seriales vs. parallel) de la atención. A partir del tiempo que demora encontrar un estímulo 'diana' entre un grupo de distractores (búsqueda visual) se ha estimado que los cambios pueden realizarse rápidamente (en menos de 40 ms). A partir del tiempo que se mantiene la interferencia producida en el reconocimiento de objetos que se presentan serial y brevemente se ha estimado que los cambios son mucho más lentos (sobre los 0.5 s). En este trabajo empleamos un nuevo método que combina la naturaleza multiobjeto presente en la búsqueda visual y el estricto control temporal propio de la presentación serial rápida. Se presentan dos barras superpuestas, y se mide el tiempo necesario para discriminar con precisión dos eventos (cambios de forma) que ocurren sucesivamente en las puntas de las barras. Cuando ambos eventos ocurrieron en la misma punta no se produjo interferencia en su discriminación. Los cambios de la atención entre partes diferentes de un mismo objeto demoraron menos de 300 ms. Sin embargo, los cambios de la atención entre objetos distintos tardaron más de 500 ms. El tiempo necesario para que la atención cambie no es constante, sino que depende de la organización perceptual local. Por tanto, parte de la controversia mencionada anteriormente pudiera deberse a las diferencias de la organización de la escena entre ambos diseños en contradicción. En la búsqueda visual, varios elementos pueden ser agrupados, mientras que en la presentación serial nos enfrentamos a un único objeto en cada instante.

Dependence of attentional shift times on local scene organization

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Abstract

The processing of natural scenes requires the reallocation of attention among objects. Measures of the duration of these attentional shifts are discrepant, supporting different theories (serial vs. parallel) of attention. Fast shifts (down to 40 ms) are estimated from the time that it takes to find a target among distracters (visual search). Slower shifts (about 500 ms) are estimated from the interference between recognition of serially and briefly presented objects. Here a novel method combines the multi-object nature of visual search, and the controlled timing of rapid serial presentation. Two overlapping bar shapes were presented. The time needed to accurately identify two successive shape changes in the tips of the bars was measured. No interference was found for events at the same tip. Shifts of attention between different parts of the same object took less than 300 ms, but between objects took over 500 ms. The time needed for attentional shifts is not constant, but depends on local perceptual organization. Duration of shifts depends not only on the difficulty of processing one event, but also the ease of capturing a new one. Part of the mentioned controversy could be due to differences in scene organization between paradigms. In visual search, multiple items can be grouped, whereas in serial presentation we deal with one object at a time.

Running title: Attentional shifts and scene organization
Keywords: Attention, vision, objects, masking, perceptual organization

The control, timing, and underlying neural mechanisms of attentional reallocation have generated a great deal of interest, although considerable disagreement persists even on basic issues (Egeth & Yantis, 1997; Desimone & Duncan, 1995). The time it takes to shift attention between aspects of a scene has been studied in two different paradigms that yield highly discrepant results: visual search and rapid serial visual presentation (RSVP).

In visual search tasks, a target object embedded in a set of distracters must be found. The time spent per item in the display has been estimated in numerous studies (reviewed in Treisman, 1988; Wolfe, 1998). Under some conditions (e.g. finding conjunctions of certain features), the reaction time for target detection increases as the number of elements in the display grows. If a strictly serial search is assumed, then dwell time estimates down to 40 ms/item have been obtained. Visual search has the virtue of simulating the multi-object nature of natural scenes. Moreover, the possible influence of perceptual organization on attentional shifts can be examined in this paradigm (Bilsky & Wolfe, 1995; Kim &Cave, 1999). However several assumptions underlying these estimates, including serial processing, are debatable. Limited-capacity parallel models can also explain the data obtained from visual search tasks (Townsend, 1990; Palmer & McLean, 1995).

Very different estimates of the timing of attentional shifts have been obtained with RSVP of alphanumeric characters. If a target is recognized within a stream of stimuli flashed briefly in rapid succession, processing of a subsequently appearing target is hampered until several hundred milliseconds have transpired (Raymond, Shapiro & Arnell, 1992; Shapiro, Raymond & Arnell, 1994). This phenomenon has been dubbed the attentional blink (AB). Using a minimal RSVP with only two stimuli, a long-lasting impediment in the identification of the second stimulus is also found (Duncan, Ward & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996). In both variants the interference is found only when attention is paid to the first stimulus. The duration of this interference can be as long as half a second (but see Moore, Egeth, Berglan & Luck, 1996). These estimates are substantially longer than the attentional dwell time inferred from visual search tasks.

RSVP allows a precise timing of the availability of visual information arising from each object, therefore the measurement of attentional shifts are more direct than in visual search. Note however, that in RSVP the objects have short lifetimes, and usually come one at a time. This is very different from the multi-object nature of natural scenes. In real world scenes most objects are relatively long lived and attention may have to shift between aspects or events affecting the same part of an object, different parts of the same object or different objects. In contrast with visual search, RSVP has the disadvantage of precluding studies concerning perceptual organization of a scene.

One limitation of both visual search and RSVP is the confounding of different sources of delay that could operate during re-deployments of attention. Attentional shift times could be due to the tying up of attentional resources by the first stimulus, to the time taken to shift attention to the second stimulus, and to difficulties in engaging the second stimulus. In the typical RSVP experiment it is difficult to disentangle these sources of delay.

Here a novel method is presented that combines the multi-object nature of visual search, and the controlled timing of visual input from RSVP. This paradigm, we which have named rapid serial object transformations (RSOT), consists of presenting several objects simultaneously in a display and measuring the accuracy in recognition of events that transform these as a function of the duration of the interval between events. As in RSVP, the duration of attentional shifts can be directly measured from the persistence of interference between the recognition of two successive events. As in visual search, the perceptual organization of scene can be manipulated by varying the relationship between objects or features. As we show below, RSOT also allows a more fine-grained assessment of the factors contributing to attentional shift times.

In the experiments described herein, two overlapping bar shapes (see Figure 1) were presented for relatively long intervals. Two successive shape changes in the tips of the bars were then presented (the stimuli used here were inspired by Behrmann, Zemel & Mozer, 1998). These changes transformed the objects (by varying the number of bumps at the tips) without destroying their identity. Accuracy in identifying the form changes was measured as a function of the time elapsed between two such events. It was therefore possible to estimate the timing of same-place, within-object, and between-object attentional shifts.

The two bars, one red and the other green, were drawn in an 'X' configuration upon a black background on a sVGA computer monitor (see Figure 1). The monitor was controlled by a 90 MHz Pentium based PC. The bars were about 8.53 degrees long and 2.63 degrees wide and were outlined in yellow. A small fixation circle (with diameter of about 28 arcmin) was placed at the center of the intersection of the two bars. Note that corners from the same bar were farther apart than corners from different objects.

The participants in the experiment were 14 volunteers in the main experiment and 12 in each control group, all university graduates working at a research institute, with ages ranging from 23 to 39 years. Sex was roughly balanced in each group, and only two were left handed (ascertained by self-report). All the subjects had normal or corrected-to-normal visual acuity, reported no color vision abnormalities, and had no history of neurological disorders.

In the main experiment each trial (see Figure 1) was structured as follows. First, a baseline stimulus was presented in which the two- and three-bump terminations were overlapped (premasked). Participants were instructed to maintain fixation on the central circle. The color of the fixation circle was a valid pre-cue of which object (the one with the same color) would be affected by the first event. On the contrary, this cue was uninformative on the location of the second event. After free inspection, the participant initiated the trial by pressing the spacebar of the computer keyboard. After 500 ms, one of the superimposed terminations was erased (thus unmasking the other) during 100 ms. This was the first event. Then the masked configuration was presented for intervals of 0, 200, 400, 700, and 1000 ms (corresponding with inter-event SOAs of 100, 300, 500, 800, and 1100 ms respectively). Then a second event consisting of the unmasking of either two or three bumps for 100 ms was presented. Finally, the premasked baseline was presented again for another 500 ms. To finalize the trial, participants were asked to report the number of bumps unmasked within each event. Responses were made via the keys F2/F3 of the computer keyboard, in the same order as the events reported. Accuracy was emphasized over response speed. Incorrect responses were signaled by a 500 ms beep on the computer loudspeaker.

Place Figure 1 about here

The three experimental conditions depended on the location of the second event respect to that of the first event. These were same-location (Figure 1A), same-object-shift (Figure 1B), and different-object-shift (Figure 1C). The first event was presented 16 times at each of the four corners for each value of SOA. The corner selected for the first event was selected pseudo-randomly on each trial. After a corner was affected by the first event, the second event was presented with equal frequency at the four corners. Repeated measure ANOVAs (and planned comparisons) were performed on the percent correct scores across subjects. The Greenhouse-Geisser correction was used when appropriate in which case the epsilon values are reported. Since the color or position of the tip in the subsequent analysis did not significantly affect accuracy in the task, data is collapsed over these factors in this report.

The identification of form change on the first event was correct in about 80 % of the trials (Fig. 2), with no influence of Condition or SOA. If a second event occurred at the same tip as the first, the reports were also accurate and did not differ significantly with SOA. Also, accuracy for same-place second events and for first events did not differ significantly at any SOA (Fig. 2). In contrast there were deficits in identifying the second form change if it affected a different place than the first event (Fig. 2) at short SOAs. At 100 ms, the under-performance was of equal magnitude (a drop of about 13 % compared to first event discriminations) for within- and between-object attentional shifts. Performance recovered for larger SOAs. These effects were confirmed by an ANOVA on the percent-correct scores with Condition (1st event , 2nd event/same place, 2nd event/within object, and 2nd event/between object) and SOA (5 levels) as principal effects. The main effects of Condition, $\underline{F}(3, 39) = 10.6$, $p<0.0003$, $\varepsilon=0.74$, and SOA, $\underline{F}(4, 52) = 15.0$, $p<0.00001$, $\varepsilon=0.61$, were highly significant. The interaction of these two factors was also significant, $F(12, 156) = 3.0$, $p<0.01$, $\varepsilon=0.5$. No effect was significant for an ANOVA restricted to the scores for the first events and same place second events.

Place figure 2 about here

Accuracy recovered as a function of SOA at different rates for within-object and between-object attentional shifts. For within-object attentional shifts, discrimination of the second event was significantly less accurate than for the first event only at 100 ms ($F(1,13)=37.8$, $p<0.00004$). For between-object attentional shifts, identification of the second event was less accurate than for the first event with SOAs of 100 ms ($F(1,13)=28.1$, $p<0.0002$), 300 ms ($F(1,13)=22.6$, $p<0.0004$), and 500 ms ($F(1,13)=7.4$, $p<0.02$). The shorter attentional shift time for within-object compared to between-object transitions was not due to the relative distance between events, since the two tips of different objects were closer than tips from the same object. Performance on the within-objects trials was equivalent for the occluded and occluding bars.

An additional experiment was performed with three groups of participants. The aim was to gauge the dependence of the results from the main experiment on the perceptual organization, and the nature of the events used. The same procedure as in the main experiment was used except that the event duration was 150 ms, and the SOA between events was fixed at 500 ms. We assumed that performance at this SOA would serve as an estimate of the speed of the attentional shift. One group was tested with the original stimuli. In another group, the tips of the bars were separated into independent objects during all the trial (Fig. 3A). The colored pixels corresponding to the broken fragments were regrouped into a circle. Therefore, the distinction of within- and between object shifts was lost, although tips were still paired by color. In the third group the event to be detected was the shape of a briefly flashed rectangle, abruptly superimposed on a tip of one bar (Fig. 3B). The event in this case did not correspond to the shape modification of an old object, but to the creation and disappearance of a new one.

Place figure 3 about here

Judgments on first events were accurate and did not differ significantly as a function of condition or group. Furthermore, there was no loss of accuracy for same-place second events (Fig. 4). In a ANOVA using Group as a between-subject factor and Event (1^{st} event vs. 2^{nd} event/same place) as a within-subject factor, there were no significant effects. However, interesting variations were found for the scores of within- and between-object second event. Observation of the average accuracy scores (Fig, 4) shows that in the group presented with the same stimuli as in the main experiment the advantage of within- over between object shifts is replicated. However, this advantage is reduced in the group with fragmented bars. In the group presented with flashed bars the between-object condition has more accurate scores than the within-object condition, a complete inversion of the effects for the first group. An ANOVA restricted to the scores for second events with place changes was performed using Condition (within- vs. between-object) as a repeated measure and Group (three levels) as a between-subject factor. Condition was significant, $\underline{F}(1,27)=5.1$, $p<0.03$, and the interaction of Group and Condition was highly significant, $\underline{F}(2,27)=17.6$, $p<0.0001$.

The observed effects were confirmed by planned comparisons. In the group with the original stimuli, scores from the within-object condition were about 8 % larger than for the between object condition, $\underline{F}(1,27)=24.5$, $p<0.00004$. This replicates the main experiment. In the group with the fragmented bars, the condition equivalent to within-objects in other groups (events affected tips of the same color) did not differ significantly from the condition equivalent to between-objects (events affected tips of different colors). Therefore when the continuity of the bars (due to physical or amodal completion) was broken, the within-object advantage in time was lost. In the group with flashed rectangles the scores for the between-object condition were 5% larger than for the within/object condition, $\underline{F}(1,27)=10.5$, $p<0.003$. Or put differently, accuracy was larger for shift of attention with shortest trajectory. Therefore in this case where the task was to identify new objects unrelated to the background figures, spatial proximity was more important for the timing of attentional shifts than perceptual organization.

Place Figure 4 about here

The present study demonstrates that the time taken to shift attention within a scene is not constant but depends critically on local perceptual organization. Here, the persistence of the interference between identification of two events is used as a measure of these switch times. Successive events affecting the same part of an object were easily identified at intervals as small as 100 ms. The duration of attentional shifts between events at different parts of the same object. have an upper bound of duration at 300 ms, whereas the equivalent interval for events concerning different objects had a lower bound of 500 ms. A related result has been obtained in a RSVP experiment. When the successive stimuli in RSVP are perceived as a single rotating object, the AB is diminished (Raymond, personal communication).

These findings are not explainable by an attentional spotlight moving at a certain speed over different distances (Tsal, 1983). The two tips of the same object were actually farther away in space than tips from different objects, yet within-object attentional shifts were faster than between-object shifts. Alternative, non-attentional explanations are also implausible. One alternative is perceptual masking, which increases with spatial proximity (Enns & Di Lollo, 2000). This property of masking is inconsistent with the fact that pairs of events at the same place had the least interference. Memory limitations and response conflicts (Pashler, 1994) are also excluded since they would affect all types of trial equally.

In the control experiment using fragmented bars as stimuli, any attentional transition between different tips took the same time. This shows that object continuity was necessary for the object based advantage to emerge, and that perceptual grouping due to color had a weaker influence. Note that physical object continuity (uniform connectedness) and amodal completion of the occluded bar were equally conductive to a within-object speed up of attentional shifts. Therefore this modulation probably occurrs at a stage of perception where the surface structure of the scene is already sorted out (Nakayama, He, & Shimojo, 1995).

A reversal of effects was obtained in the other control condition using flashed rectangles, where the between-object shift was faster than the within-object shift. A simple explanation for this result is that the speed of the shifts was governed by spatial proximity (Hoffman & Nelson, 1981; Hoffman, Nelson & Houck, 1983). This finding shows that the influence of perceptual organization on attentional reallocations can be overridden by abruptly presented and salient stimuli. Shape mutations and sudden onset stimuli may have these divergent effects on attentional shifts because they affect scene organization in different ways. The tip transformation events used in the main experiment do not modify the number of objects within the scene. In other words, they do not create new or destroy old object-files; they just update the content of the existing files (Kahneman, Treisman & Gibbs, 1992). A briefly flashed rectangle, that is extraneous to the previous organization of the scene, can be considered as the creation of a new object-file. Yantis (1996) has argued that new objects can capture attention automatically.

The faster shifts of attention for within- compared to between-object conditions is congruent with previous studies of object-based attention. Two attributes of one object can both be judged accurately at once, whereas there is interference between judgments of two attributes from different objects (Duncan, 1984; Vecera & Farah, 1994; Lavie & Driver, 1996; Behrmann et al , 1998). By using the RSOT paradigm, we extend this finding into the temporal domain. Congruent results have been obtained in another variant of RSOT with moving stimuli. Two events modifying one component of transparent motion can be discriminated without interference, whereas recognition of events affecting different components of transparent motion are subject to interference for temporal separations up to about 600 ms (Valdes-Sosa, Cobo & Pinilla, 2000). However, once attention is assigned to an object, not all of its parts (and events that affect them) are processed with equal priority. The segmentation of a scene has a hierarchical organization, with objects identifiable as parts of other objects (Vecera, Behrmann & Mc Goldrick, 2000). A previous study has shown a cost in processing two different parts of the same object compared to the same part.

The present study offers a solution for the discrepancy between estimates of attentional shift times from visual search and from RSVP. On one hand, between-object attentional shifts have a similar time course to the AB. On the other hand, the slope of reaction time against numbers-of-items may underestimate the dwell time (Moore, et al 1996). In visual search not all items are processed, and some items may be grouped together for access to (Treisman, 1982; Bundesen & Pedersen, 1983; Egeth, Virzi & Garbart, 1984) or for rejection from attention (Duncan & Humphreys, 1989). Dwell time in most search experiments could be somewhere between 50 and 200 ms (Moore, et al 1996), and a recent study using ERPs in a modified search task proposes a number close to 100 ms (Woodman & Luck, 1999). These revised estimates are close to the within-object shift times found in the present study. We have shown here that the time needed for an attentional shift is not constant, but depends on local perceptual organization. A single ' true' value for the dwell-time' does not exist. Part of the discrepancy about estimates of attentional shift times could be due to differences in scene organization between paradigms. In visual search, multiple items can be grouped in different ways, whereas in RSVP we deal with one object at a time.

As mentioned above, attentional shift times could encompass release from first stimulus, shifting of attention to the second stimulus, and capture of the second stimulus. In the visual search literature (Wolfe, 1998), dwell time usually means the time spent on each element, and is supposed to reflect the difficulty in identifying each stimulus. Here, all first events were equivalent in nature and difficulty. The subjects could not predict beforehand where the second event would occur on each trial. Therefore, differences in attentional shift times are not related to different speeds of release from the first object. This is congruent with the finding that the duration of the AB is not influenced by difficulty of T1 recognition (Raymond, Shapiro & Arnell, 1992; Ward, Duncan & Shapiro, 1996). The growing shift times from same-place, to within-object, and to between-object pairs of events must therefore arise from differences in either the duration of the shift itself, or in the ease of engaging the second event.

We favor the last alternative as a natural consequence of competition for limited attentional resources within an organized scene (Humphreys & Duncan, 1992). When attention is drawn to the first event, resources are withdrawn from other parts of the scene (as part of a competition between object representations). This re-distribution is graded, with different parts of an object loosing some resources, but with items from completely different objects loosing much more. Note that this explanation implies that at the same time that the first event is being processed, an active redistribution of attention is occurring across the scene, and that the resulting status of unattended items is not equivalent, but varies according to object organization. Therefore delays in shifting attention originate not only from processing being tied up by an attended object, but also on inhibition (resulting from competition) that affects unattended objects.

We have shown that RSOT has features that allow the influence of local scene organization on attentional shift times to be studied. Beyond the experimental convenience of RSOT, it also interesting because it captures processes that are relevant to real world abilities. We frequently are faced with scenes composed of entities that are relatively stable but suffer mutations (henceforth, the term event is used for modifications of parts of a scene that do not change its overall organization). We may be taxed to detect successive events affecting the same part of an object (i.e. sequential lip movements of a speaker), or successive events on different parts of the same object (i.e. gestures and lip movements from the same person), or even events from different objects (i.e. lip movements from two people trying to speak at once). Additional RSOT studies are under way with more complex scenes and event related potential recordings.

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Figure legends

Figure 1. Stimulus layout and time chart.

Each trial began with a masked baseline, in which each tip of the bars presented two- and three-bump terminations overlapped, displayed for 500 ms. Then, one of the superimposed terminations was erased unmasking the other (exposing two or three bumps) during 100 ms. This was the first event. Then the masked baseline was presented for variable time intervals (SOAs between the two events). Then a second event for 100 ms was presented. Finally, the masked baseline was presented again for another 500 ms. The three experimental conditions depended on the location of the second event respect to that of the first event. In the examples, which correspond to the three experimental conditions, the first event affects the upper left tip. The conditions were: A) same-location, with the second event at the same place as the first, B) within-object-shift, with the second event in the example at the lower right corner, and C) between-object-shift, with the second event in the example at the lower left corner.

Figure2. Accuracy for different types of trial as a function of inter-event SOA.

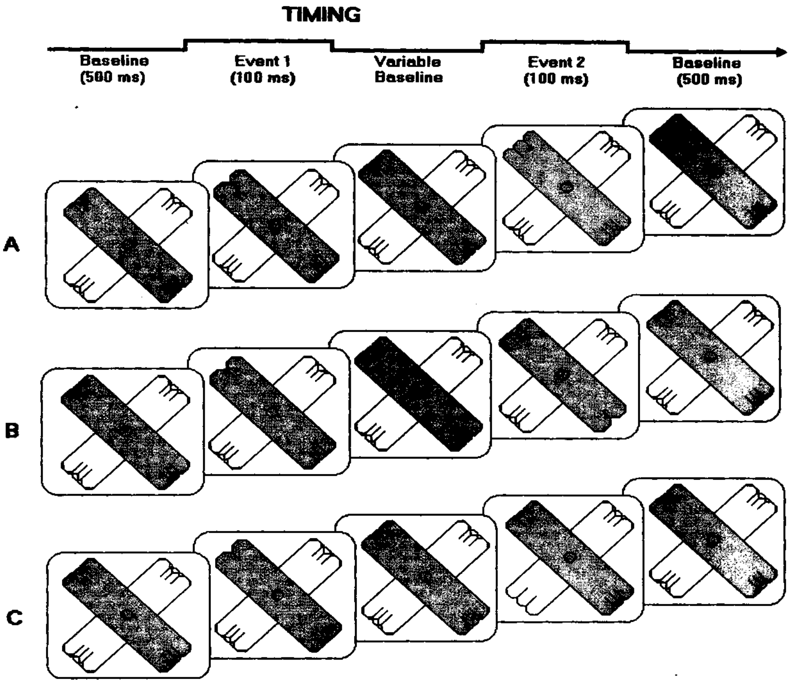
The average percent-correct discrimination of events plotted against the SOA between events for each condition. The points represent the average of data from 14 participants, and are collapsed across the tip at which the events occurred. Each curve corresponds with a different condition. Since accuracy for the first event did not vary significantly with condition, for this event the data is collapsed across conditions.

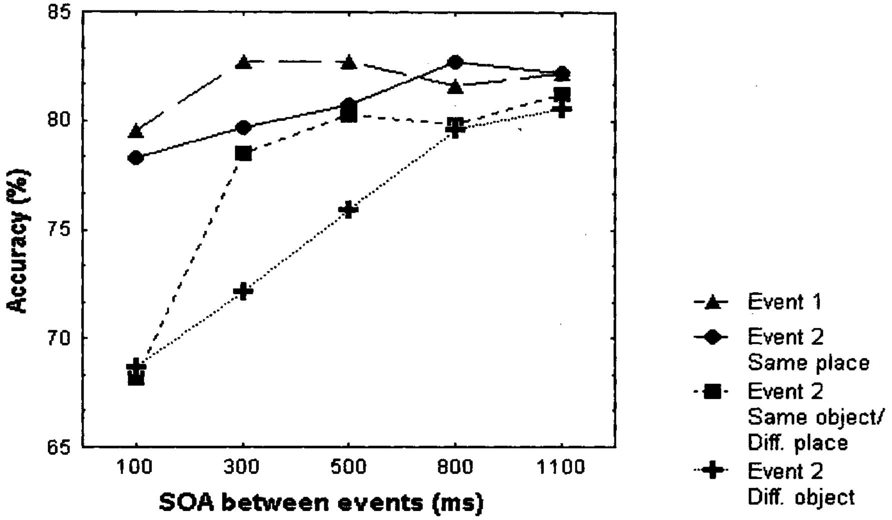
Figure 3. Stimuli for the control experiments.

A) The tips of the bars were broken off to form four separate objects to eliminate perceptual grouping between the tips that formerly belonged to the same bar. In order to maintain the same overall luminance level and color proportions as in the main experiment, a circle was drawn at the center containing exactly the same number of red and green pixels as the missing parts of the bars. B) The baseline was the same as in the main experiment, but the events were rectangular shapes briefly flashed at the tips of the bars. The rectangles could be larger in height than in width (vertical) or vice versa (horizontal). Subjects had to discriminate if the rectangles were either vertical or horizontal.

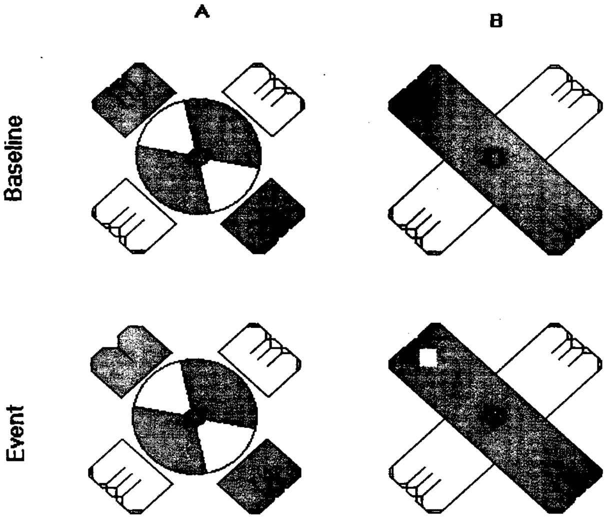
Figure 4. Plot of accuracy in the control experiment for each group.

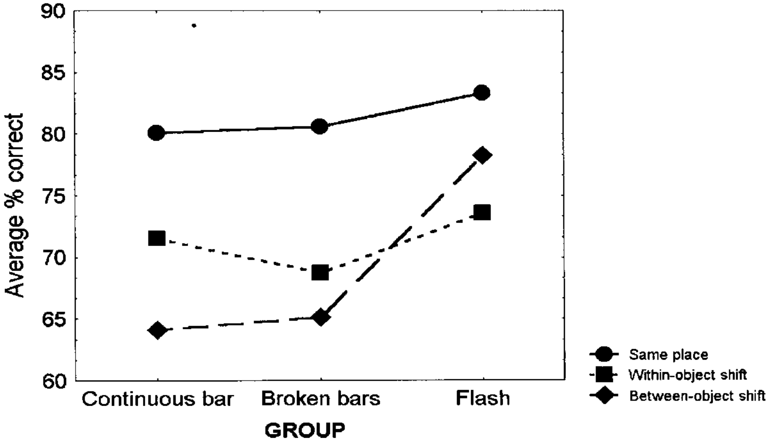
The average accuracy (percent correct responses) in recognizing the second event in the control experiment is plotted for each group of subjects. The different curves correspond to the types of trial according to where attention had to shift respect to the first event. Continuous bars refer to the group presented with the same background as in the main experiment (Figure 1). Broken bar refers to the group presented with isolated tips separated by a circle (Figure 3A). Flash refers to the group where the events consisted of flashing a rectangle (Figure 3B).


TIMING
Baseline (500 ms)
Event 1 (100 ms)
Variable Baseline
Event 2 (100 ms)
Baseline (500 ms)
A
B
C


85
80
75
70
65
Accuracy (%)
100
300
500
800
1100
SOA between events (ms)
Event 1
Event 2 Same place
Event 2 Same object/ Diff. place
Event 2 Diff. object

Control Experiments





90
85
80
75
70
65
60
Average % correct
Continuous bar
Broken bars
Flash
GROUP
Same place
Within-object shift
Between-object shift

Descripción de los experimentos (diseños experimentales y resultados principales)

Estudios con superficies transparentes

Uno de los dos diseños experimentales empleados en esta tesis se basa en la transparencia. La transparencia es un fenómeno consistente en la posibilidad de ver más de un objeto en una misma línea de visión. Puede ser generada artificialmente a través de la estereopsis, definiendo estereogramas de puntos aleatorios a diferentes planos de profundidad (Akerstrom y Todd, 1988; Weinshall, 1989), o mediante el movimiento relativo, desplazando dos conjuntos de puntos en direcciones diferentes en la misma región del espacio visual (Snowden, Treue, Erickson y Andersen, 1991; Andersen y Wüestefeld, 1993; Qian, Andersen y Adelson, 1994). No obstante, es necesario aclarar que el movimiento transparente utilizado en nuestros experimentos no es sólo un artificio creado en el laboratorio, sino que aparece en situaciones reales de la naturaleza. Se pone de manifiesto cuando un objeto discontinuo se mueve bloqueando parcialmente la visión de otro objeto (por ej.: un animal que se esconde entre la hierba, o una fruta que se nos pierde en el follaje). Otro ejemplo común es la proyección de sombras y reflejos sobre otros objetos.

El movimiento de superficies transparentes induce una percepción clara de dos superficies que se deslizan una sobre la otra y, más allá de su validez ecológica, resulta de gran valor metodológico por dos razones fundamentales: Por una parte, algunos autores plantean que la organización perceptual de una escena visual se estructura básicamente en superficies, siendo éstas las representaciones sobre las cuales opera la selección atencional (He y Nakayama, 1995); al mismo tiempo, es posible considerar a las superficies como objetos. Por la otra, un diseño que utilice el movimiento de superficies transparentes permite combinar las tres aproximaciones que han intentado aislar la atención orientada a los objetos de la atención espacial: 1) Ambas superficies generadas por el movimiento transparente se encuentran superpuestas en la misma región del espacio; 2) Los elementos que pertenecen a las distintas superficies pueden estar más cercanos espacialmente que aquellos que se agrupan en una misma superficie; 3) Los elementos, al moverse, se disocian de cualquier localización espacial particular.

La primera variante utilizada (artículo 1) consistió en desplazar simultáneamente, en dos direcciones diferentes, dos conjuntos entremezclados de puntos; ambos conjuntos tenían distinto color e igual luminancia. La conjunción particular de cada color y dirección del movimiento, creaba las dos superficies transparentes (figura 1). Un subconjunto mayoritario de los puntos que conformaban cada superficie se movía coherentemente en una dirección específica (dominante), en tanto el resto se movía aleatoriamente hacia otras direcciones. A su vez, la velocidad del movimiento podía ser más lenta o más rápida. Los sujetos siempre debían discriminar simultáneamente la misma pareja de atributos (velocidad y dirección dominante) relativos al movimiento. El aspecto crítico consistió en que ambos atributos podían estar referidos al movimiento de una sola superficie (primaria), o al movimiento de ambas.

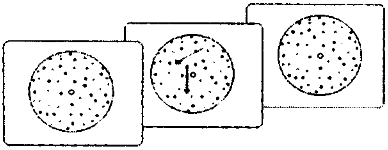


Fig. 1. Los conjuntos de puntos, rojo y verde (representados en negro y gris), se presentaban sobre un fondo negro, y se desplazaban brevemente, cada uno en una dirección diferente (indicada con las flechas correspondientes). Los sujetos debían discriminar simultáneamente la velocidad y la dirección del movimiento de uno de los conjuntos, o la velocidad del movimiento de uno y la dirección del movimiento del otro. La superficie primaria (aquella a la que debía atenderse con prioridad) se preavisaba con el color del punto de fijación.

Los resultados obtenidos evidenciaron que, contrario a lo que predicen los modelos espaciales clásicos (metáfora del reflector), no es posible atender simultáneamente a atributos correspondientes a diferentes superficies, a pesar de ocupar ellas la misma región del espacio (figura 2). Esta interferencia en la discriminación de atributos pertenecientes a superficies diferentes crecía a medida que disminuía la duración del movimiento.

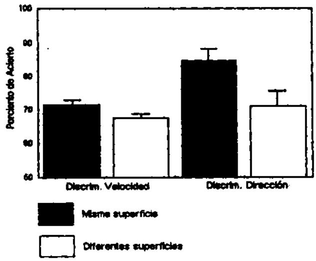


Fig. 2. Cuando se discriminaba la velocidad del movimiento de una de las dos superficies, existía una mayor precisión en la discriminación simultánea de la dirección de ese mismo movimiento, que en la discriminación simultánea de la dirección del movimiento que ocurría en la otra superficie

La segunda variante de este diseño (artículo 2, exp. 1) se corresponde con el método de las Transformaciones Seriales y Rápidas de Objetos (TSRO), descrito en la introducción. Tenía como propósito estudiar la atención a dos eventos sucesivos que modificaban objetos (superficies) preexistentes, así como la distribución de dicha atención en el tiempo. Con ese fin se realizaron las siguientes modificaciones: Se introdujo una línea de base, previa a los eventos, durante la cual ambos conjuntos de puntos rotaban en sentidos opuestos para lograr la segregación de las superficies, y se pre-avisaba en cuál de ellas ocurriría el primer evento dirigiendo la atención hacia la misma (figura 3). Ambos eventos consistían en desplazamientos lineales breves (en las cardinales y diagonales), similares a los descritos en la variante anterior, pero no diferían en velocidad y ocurrían secuencialmente. El tiempo entre ambos eventos era variable, presentándose nuevamente durante ese período la línea de base, con el doble objetivo de mantener la organización perceptual y enmascarar el primer evento. Tras el segundo evento se presentaba otra vez la línea de base. Los sujetos debían discriminar la dirección de ambos eventos, pudiendo éstos ocurrir en la misma superficie (figura 3A) o en superficies diferentes (3B).

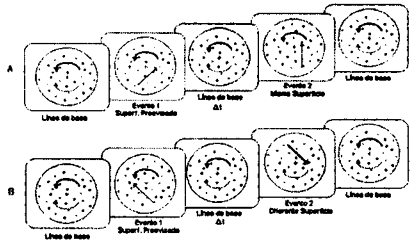


Fig. 3. Ambos conjuntos de puntos rotaban en sentido contrario durante la línea de base (señalado con flechas). Ambos eventos consistían en desplazamientos lineales breves de uno de los conjuntos mientras el otro continueba rotando (señalado con flechas), y el tiempo entre ellos era variable. Los sujetos debían discriminar la dirección del movimiento de dos eventos sucesivos que ocurrían en el mismo conjunto (A), o en conjuntos diferentes (B). La superficie a atender (aquella en la cual ocurriría el primer evento) se preavisaba con el color del punto de fijación.

Los resultados indican que aunque es posible atender a dos eventos breves que afectan la misma superficie para cualquier intervalo temporal entre el comienzo de los mismos, esto no resulta posible cuando los dos eventos afectan superficies diferentes y el intervalo es menor que 0,5 segundos (figura 4). Existía un costo asociado al cambio de superficie, el cual se reflejó en una peor discriminación del segundo evento si éste ocurría en

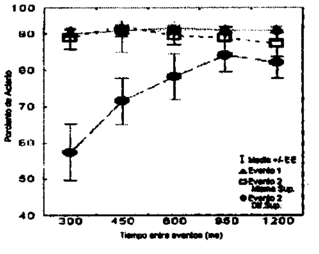


Fig. 4. La discriminación de la dirección del movimiento en el primer evento fue muy precisa. La discriminación de la dirección del movimiento en el segundo evento fue igualmente precisa cuando éste ocurría en la misma superficie en la que había ocurrido el primero, independientemente del tiempo transcurrido entre ambos eventos. Si el segundo evento ocurría en la otra superficie, la discriminación de la dirección del mismo se veía afectada si el tiempo transcurrido entre ambos eventos era inferior a 500 miliseg.

una superficie distinta. Esto indica que la atención tarda un tiempo relativamente largo en desplazarse de una superficie a otra. Esta demora no está bajo el control voluntario del sujeto (artículo 3).

A partir de los resultados anteriores, se fijó el intervalo de tiempo entre ambos eventos en un valor (450 ms) para el cual se observaron claramente los efectos atencionales descritos. Varios controles experimentales mostraron que la prioridad otorgada a los eventos favorecidos no se debía a factores espaciales, o a filtros sensoriales de bajo nivel. Entre las alternativas rechazadas se encontraban una selección basada sólo en el color, el contenido de frecuencia espacial, o la separación subjetiva de las superficies en profundidad (artículo 2, exps. 3-4). Incluso la separación de las superficies en el espacio, lejos de incrementar, reduce el costo debido al tránsito de la atención, lo cual contradice las predicciones de cualquier modelo espacial (artículo 2, exp. 2).

En otro estudio realizado con este mismo diseño, pero con la particularidad de que el segundo evento se producía sólo en la mitad de los casos, se demandaba de los sujetos la discriminación del primer evento y la detección del segundo, en lugar de dos discriminaciones sucesivas (artículo 4, exp. 1). Utilizando la Teoría de Detección de Señales (TDS), para el análisis de los aciertos y las falsas alarmas en la tarea de detección para cada condición, se midió la capacidad de detección sensorial (d´) de los estímulos, asociada con procesos pre-perceptuales tempranos y descontaminada de los procesos decisorios más tardíos. Los resultados demostraron que la dificultad para desplazar la atención entre las superficies se expresa no sólo en la discriminación de los eventos, sino también a un nivel más básico de procesamiento, pues se reduce la capacidad de detección sensorial (d´) de los eventos que transforman la superficie no atendida.

Esta misma variante experimental se utilizó (artículo 4, exp. 2) en un estudio de potenciales relacionados a eventos (PRE), más específicamente aquellos relacionados con el inicio o el cambio en la dirección del movimiento (PR-IM), y en particular el primer componente negativo (N1 ó N200). La señal se sincronizó con el comienzo del primer evento, y se registró el EEG con un montaje posterior (Pz, Oz, P3, P4, T5, T6, O1, y O2) con referencia en ambos lóbulos de las orejas interconectados. Se registró además el EOG, rechazándose luego, mediante inspección ocular, aquellos segmentos que presentaron artefactos o actividad excesiva en los electrodos de EOG.

Como el intervalo entre ambos eventos era muy breve, la señal provocada por el primer evento se superponía a la provocada por el segundo (señal de interés). Se obtuvo la señal provocada por el primer evento en aquellas pruebas en las cuales sólo se presentó éste, con el propósito de obtener el potencial diferencia correspondiente al segundo evento aislado. Los resultados demostraron que los eventos que ocurrían en la superficie no atendida provocaban un componente N1 más reducido que los eventos que afectaban la superficie atendida (figura 5). Los resultados obtenidos, tanto a partir de la TDS como de los PRE, indican un estadio pre-perceptual para este efecto atencional.

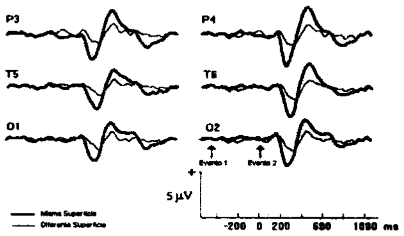


Fig. 5. Aquí se muestra el gran promedio entre sujetos del potencial diferencia correspondiente al segundo evento aislado, en 6 de las derivaciones empleadas (O1, O2, T5, T6, P3 y P4). Se encuentran superpuestas las señales obtenidas cuando dicho evento ocurrió en la misma superficie que el primero (línea gruesa) y cuando ocurrió en la otra superficie (línea fina). Las flechas indican el momento de inicio de ambos eventos, y el cero en el eje temporal coincide con el inicio del segundo. Se observa una marcada reducción de la amplitud de N1 en la señal correspondiente al segundo evento cuando éste ocurría sobre una superficie diferente de aquella donde ocurrió el primero.

Se desarrolló otro estudio de PRE (artículo 5), realizando varias modificaciones en el diseño experimental. Con la línea de base de fondo, se presentó serial y rápidamente una gran cantidad de eventos que afectaban aleatoriamente una u otra superficie, elevándose la carga perceptual. Los desplazamientos en las direcciones cardinales se utilizaron infrecuentemente (20% de los eventos), en tanto los desplazamientos en las direcciones diagonales se utilizaron frecuentemente (80% restante). Se realizó una tarea de atención sostenida en la cual los sujetos debían atender a una de las dos superficies, y discriminar los eventos infrecuentes que ocurrían en ella. Luego se compararon las señales provocadas por los eventos frecuentes que modificaban la superficie atendida con los que transformaban la no atendida.

Los resultados mostraron una supresión casi completa de los componentes P1 y N1 provocados por los eventos que ocurrían en la superficie no atendida, sin afectación de los componentes provocados por los eventos que ocurrían en la superficie atendida (figura 6A). En varios experimentos controles se demostró que si durante la línea de base ambos conjuntos de puntos estaban estáticos o rotaban en el mismo sentido (6B), fusionándose ambas superficies en un único objeto bicolor, desaparecían los costos para reubicar la atención entre superficies, y también desaparecía la modulación de los componentes tempranos P1 y N1.

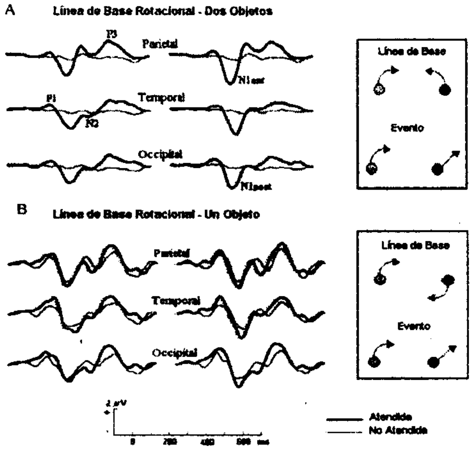


Fig. 6. Se comparan los potenciales provocados por los eventos frecuentes (atendidos y no atendidos superpuestos) cuando se utilizaron dos líneas de base diferentes: ambos conjuntos rotaban en direcciones opuestas segregándose en dos superficies (A), o rotaban en un mismo sentido percibiéndose como una sola superficie bicolor (B). En la columna de la izquierda se representan las derivaciones P3, T5 y O1; en la columna de la derecha, P4, T6 y O2. El panel a la derecha de la figura representa que sucedía en cada conjunto durante la línea de base y los eventos. Se observó una gran supresión de los componentes P1 y N1 en A, mientras que tal supresión no se produjo en B.

Estudios con figuras

Si bien el movimiento transparente es metodológica y ecológicamente válido, es cierto que abarca un diapasón estrecho de fenómenos visuales. Era necesario entonces descartar la posibilidad de que los resultados vistos hasta aquí fueran específicos sólo para el caso particular del movimiento transparente. Por otra parte, el diseño anterior se proponía eliminar cualquier contribución espacial, por lo que no permitía explorar las influencias del espacio en los desplazamientos de la atención (intra e inter-objeto) en el tiempo.

En un nuevo tipo de estudio también se utilizaron las Transformaciones Seriales y Rápidas de Objetos (TSRO). Se presentaron dos figuras alargadas en forma de barras de distinto color, cruzadas en forma de 'X' ocluyéndose una a la otra (artículo 6). Las puntas de las barras presentaban una máscara compuesta por la superposición de dos patrones (formas). Cada evento consistía en un breve desenmascaramiento de uno de estos patrones en una de las puntas de una de las barras. Dos eventos se sucedían en cada prueba, pudiendo ambos ocurrir en la misma punta (figura 7A), en las dos puntas de una misma barra (7B), o en dos puntas de barras diferentes (7C).

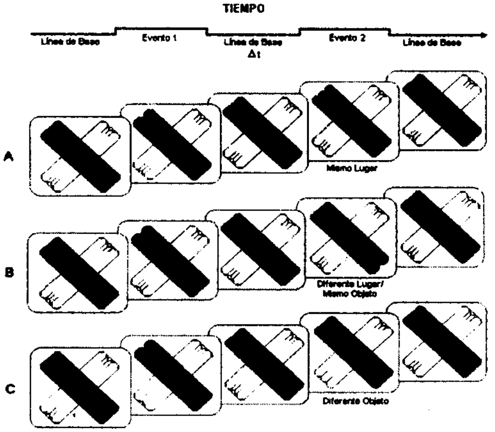


Fig. 7. Se presentaban dos barras, una roja y una verde (representadas en gris y blanco), cruzadas en forma de 'X' sobre un fondo negro. Debía atenderse a aquella barra, preavisada con el color del punto de fijación, donde ocurriría el primer evento. Los extremos de las barras estaban enmascarados durante la línea de base. Cada evento consistía en el desenmascaramiento breve (aparición de un patrón) en uno de los extremos de una de las barras, y el tiempo entre ellos era variable. Se exploraron 3 condiciones: ambos eventos ocurrían en el mismo extremo de una barra (A), en extremos diferentes de una misma barra (B), o en extremos de barras distintas (C). Nótese que la distancia entre los extremos de una misma barra es mayor que la existente entre extremos de barras distintas. Los sujetos debían discriminar el patrón que quedaba descubierto en ambos eventos.

Al inicio de cada prueba se presentaba la línea de base (barras enmascaradas), durante la cual se lograba la segmentación previa de la escena y se pre-avisaba en cuál barra (pero no en cuál de los extremos de la misma) se produciría el primer evento, logrando que la atención se dirigiera a ella. El tiempo entre ambos eventos era variable, presentándose nuevamente durante ese período la línea de base, con el doble objetivo de mantener la organización perceptual y enmascarar el primer evento. Tras el segundo evento se presentaba otra vez la línea de base. Los sujetos debían discriminar el patrón que quedaba desenmascarado en ambos eventos.

Los resultados mostraron (figura 8) que es posible atender sin interferencias a dos eventos que afectan la misma parte de una barra (para cualquier separación

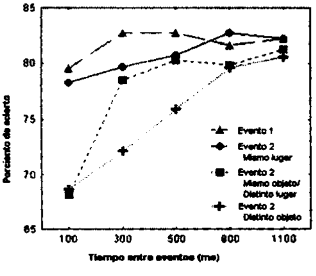


Fig. 8. La discriminación del primer evento fue muy precisa. La discriminación del segundo evento fue igualmente precisa cuando éste ocurría en el mismo lugar que el primero (el mismo extremo de una de las barras), independientemente del tiempo transcurrido entre ambos eventos. Si el segundo evento ocurría en otro lugar, su discriminación se veía afectada si el tiempo transcurrido entre ambos eventos era corto. Si, a pesar de ocurrir en un lugar diferente, el segundo evento ocurría en la misma barra, la precisión de la discriminación de éste se recuperaba al transcurrir un tiempo de 300 miliseg. entre ambos eventos. Sin embargo, si ocurría en la otra barra, la recuperación aún no era posible tras haber transcurrido 500 miliseg.

temporal). Sin embargo, esto no es posible cuando ambos eventos afectan distintas partes de un mismo objeto, o a dos objetos distintos. Es importante destacar que el tránsito de la atención entre dos partes de un mismo objeto demoró menos de 0,3 segundos, mientras que el tránsito entre objetos distintos tardó entre 0,5 y 0,8 segundos. Nótese que, debido a la forma del estímulo empleado, la distancia entre las partes de un mismo objeto es mayor que la existente entre partes de objetos distintos. Por tanto, estos resultados no son explicables por un modelo espacial.

A partir de los resultados anteriores, se fijó el intervalo de tiempo entre ambos eventos en un valor (500 ms) para el cual se observaron claramente los efectos atencionales descritos. Varios controles experimentales (artículo 6) estudiaron los efectos de modificar la organización perceptual, impidiendo la integración de las partes dentro de un mismo objeto (figura 9, izquierda) o usando eventos que capturan automáticamente la atención (9, centro). También se exploró la influencia de un pre-aviso que orientara la atención más al espacio que a los objetos derivados de la organización perceptual (9, derecha). En todos estos casos desapareció la influencia de la organización perceptual sobre la distribución de la atención a los eventos.

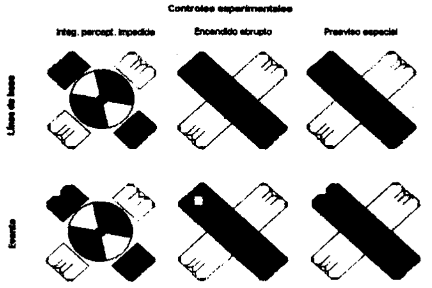


Fig. 9. Se presentan varios controles. En la columna izquierda la variación consistió en la utilización de una línea de base que impedía la integración de los extremos en barras, segregándolos en 4 objetos independientes. En el caso del centro, los eventos consistían en la aparición repentina en uno de los extremos de un rectángulo cuya posición (vertical u horizontal) debía ser discriminada. En el experimento de la columna derecha no se preavisaba una barra, sino el extremo particular de ésta donde ocurriría el primer evento.

Discusión general.

Esta tesis se propuso cuestionar el modelo hegemónico de la atención visual (metáfora del reflector) que defiende la selección basada en el espacio (Posner, 1980; Eriksen y St. James, 1986; Treisman, 1988). Como hemos visto, este modelo postula la existencia de un foco atencional unitario que selecciona una región particular del campo visual, y que se desplaza serial y rápidamente de una localización espacial a otra. Plantea, además, que esta selección es temprana, es decir, que ocurre en las primeras etapas del procesamiento visual, siendo anterior a otros tipos de selección no espacial. Afirma, por último, que las bases neurales de esta selección se encuentran en las primeras áreas extraestriadas de la corteza visual, proponiendo localizaciones posteriores en el sistema visual para los restantes tipos de selección.

Por otra parte, proponemos la utilización del método de las Transformaciones Seriales y Rápidas de Objetos (TSRO) que consiste en la presentación sucesiva de eventos breves que modifican objetos preexistentes y estables en el campo visual. La utilización de los eventos tiene varias ventajas: son más ecológicos, no capturan automáticamente la atención (Yantis, 1996), y posibilitan el estudio de la influencia de la organización perceptual sobre la dinámica temporal de los cambios de la atención. A continuación, discutiré los principales resultados obtenidos en torno a tres grandes temas:

¿Qué se selecciona?

Los resultados obtenidos en los estudios con superficies transparentes muestran que la discriminación simultánea (y sucesiva) de dos atributos o eventos pertenecientes a superficies superpuestas diferentes genera una interferencia en el procesamiento. Esta interferencia no es concebible desde el modelo espacial clásico, pues ambas superficies ocupan la misma región del espacio y no pueden ser seleccionadas por la acción de un foco unitario. En los estudios con figuras se observó que la discriminación sucesiva de eventos sufría un deterioro mayor cuando ambos eventos modificaban extremos de objetos diferentes que cuando modificaban extremos de un mismo objeto. Este deterioro tampoco se explica desde la perspectiva del modelo clásico, pues la distancia existente entre los extremos del mismo objeto es mayor que la que existe entre los extremos de objetos distintos.

Nuestros datos más bien concuerdan con otra línea de pensamiento que sostiene que es más fácil evaluar dos atributos de un mismo objeto que de dos objetos diferentes (Duncan, 1984, 1993a, 1993b; Duncan y Nimmo-Smith, 1996; Baylis y Driver, 1993; Vecera y Farah, 1994; Vecera, 1994; Lavie y Driver, 1996; Kramer, Weber, y Watson, 1997; Egly, Driver y Rafal, 1994; Behrmann, Zemel y Mozer, 1998). Según este enfoque, la atención visual se encuentra guiada por la organización perceptual de la escena (Duncan y Humphreys, 1989, 1992; Duncan, 1995; Nakayama, He y Shimojo, 1995), por lo que la selección tiene lugar entre representaciones más complejas (objetos), que se derivan de la organización perceptual, y que compiten por el control atencional.

Sin embargo, estos planteamientos han sufrido diversas críticas debido a las características de los estímulos empleados por estos autores. Se ha señalado que es posible que se estuvieran seleccionando no los objetos, sino algún otro atributo elemental (por ej.: color, contenido de frecuencia espacial, movimiento, etc.) de los mismos (McLeod, Driver y Crisp, 1988; McLeod, Driver, Dienes y Crisp, 1991; Watt, 1988; Bundesen y Pedersen, 1983; Wolfe, Cave y Franzel, 1989; Treisman y Sato, 1990; Kramer y Jacobson, 1991). La selección pudiera responder a la acción de filtros de bajo nivel que sintonizan con dichos rasgos y no estar basada en las representaciones más complejas.

La particularidad de los estímulos empleados en nuestros dos diseños, donde tanto los objetos como los eventos que los transforman son definidos a partir de atributos idénticos o equivalentes, garantizan que los efectos atencionales expuestos en esta tesis no son explicables a partir de la selección de atributos aislados. Por otra parte, controles experimentales realizados con uno y otro diseño, y en los cuales se desintegraba la organización perceptual en objetos, impidieron sistemáticamente los efectos atencionales selectivos. Por todo lo anterior, estos resultados no son explicables a partir de la acción de filtros sensoriales de bajo nivel.

Por otra parte, se han formulado variantes modificadas del modelo clásico. Una de estas variantes plantea que el foco opera en el espacio tridimensional y no sólo en el plano (Downing y Pinker, 1985; Nakayama y Silverman, 1986; Andersen, 1990, Andersen y Kramer, 1993). Podría argumentarse que la selección atencional de una de las superficies transparentes o de las barras se debe a que éstas se separan subjetivamente en diferentes planos de profundidad. Esta alternativa queda descartada en uno de nuestros controles experimentales, donde una mayor separación en profundidad de las superficies, producida a través de la estereopsis, no influye sobre los efectos atencionales. En el caso de las figuras, el que una barra ocluyera a la otra (percibiéndose por encima) tampoco tuvo efectos sobre la distribución de la atención.

Otras variantes aceptan que sobre el foco influye la organización perceptual de la escena (Vecera y Farah, 1994; Vecera, 1994; Kramer, Weber y Watson, 1997; Treisman, 1988; Treisman y Sato, 1990; Wolfe, Cave y Franzel, 1989). En una de ellas se concibe que el foco adapta su forma a la de los objetos, pero sostiene que la selección opera entre las localizaciones espaciales ocupadas por dichos objetos, basándose, principalmente, en los beneficios observados para procesar dos objetos mientras más cercanos están uno del otro (Luck, Fan y Hillyard, 1993; Kramer, Weber y Watson, 1997; Hoffman y Nelson, 1981; Hoffman, Nelson y Houck, 1983, Downing y Pinker, 1985; Laberge y Brown, 1989).

Por un lado, la superposición de las dos superficies en el primer diseño también impide la acción de focos flexibles que puedan seleccionar una de ellas siguiendo cualquier mecanismo espacial. Más aún, en uno de nuestros controles experimentales, una mayor distancia espacial entre ambas superficies, lejos de incrementar los efectos atencionales, los disminuye. Por otro lado, los resultados obtenidos con el segundo diseño muestran que los cambios de la atención de un evento a otro no están determinados por la distancia espacial existente entre las localizaciones donde dichos eventos tuvieron lugar, siendo más fácil transitar entre dos sitios pertenecientes a un mismo objeto que entre sitios de objetos distintos, aún cuando los primeros estén más distantes entre sí que los segundos. Por tanto, nuestros datos también son incompatibles con los modelos espaciales modificados.

Todos los resultados analizados apuntan hacia la selección entre representaciones más complejas que integran varios rasgos o atributos elementales, lo que implica que primero se organiza perceptualmente la escena en objetos, y después se selecciona uno de ellos. La distribución de la atención es posterior a (y está basada en) la organización perceptual (procesamiento en paralelo) de la escena visual, en la cual se forman las representaciones de los objetos.

La atención en el tiempo

Como se dijo en la introducción, la atención no puede quedar atrapada en una sola fuente de información. En los estudios con superficies transparentes se observó que la interferencia en la discriminación de un evento asociada al cambio de la atención de una superficie a otra duraba alrededor de medio segundo. Del mismo modo, en los estudios realizados con figuras, se obtuvo que la interferencia asociada al cambio atencional entre objetos distintos se mantenía por un intervalo de tiempo igualmente largo, mucho mayor a la asociada con el cambio atencional entre partes distintas de un mismo objeto. Estos efectos no son explicables a partir del modelo hegemónico del foco espacial. En el primer caso, las superficies transparentes están superpuestas en la misma región del espacio, por lo que el cambio de la atención de una a otra no implicaría un cambio del foco y, por tanto, no provocaría interferencias más duraderas. En el segundo caso, el cambio atencional entre partes distintas de un mismo objeto es más rápido a pesar de que existe una mayor distancia entre éstas que entre las partes de objetos diferentes.

Otros autores han realizado estimados contradictoriamente cortos del tiempo que tarda el cambio atencional (Wolfe, 1998). Para ello se han basado en los datos obtenidos en los experimentos de búsqueda visual, los cuales consisten en detectar la presencia o no de un estímulo "diana" en un conjunto de distractores, todos presentados simultáneamente. Este enfoque supone que cuando la búsqueda requiere atención el procesamiento es serial (de elemento en elemento). El tiempo que la atención se detiene en cada elemento se estima considerando el tiempo total empleado en la búsqueda en función del número total de elementos presentes en la escena. Ahora bien, el supuesto de que la búsqueda es serial es discutible metodológicamente. El procesamiento bien podría efectuarse en paralelo, pues todos los estímulos se presentan simultáneamente, en cuyo caso los estimados serían mayores.

Nuestras interferencias duraderas apoyan los estimados relativamente largos propuestos por otros autores que han utilizado el método de la presentación visual serial rápida (PVSR). En una de sus variantes (Duncan, Ward y Shapiro, 1994; Ward, Duncan, y Shapiro, 1996) se presentaron dos estímulos en distintas localizaciónes espaciales con un tiempo variable entre ellos. La detección del primer estímulo interfería durante más o menos medio segundo la detección del segundo estímulo, tomándose este valor como el tiempo durante el cual la atención quedaba atrapada en el primer objeto ('tiempo de estacionamiento atencional'). Otra variante consiste en la detección de dos estímulos "diana" separados temporalmente por una serie variable de elementos (distractores) presentados rápidamente (Raymond, Shapiro y Arnell, 1992; Shapiro, Raymond y Arnell, 1994). La detección del primer estímulo interfiere durante más o menos medio segundo la detección del segundo estímulo, tomándose este valor como el tiempo durante el cual la atención se encontraba ocupada en el procesamiento del primer estímulo ('parpadeo atencional'). Sin embargo, más allá de las coincidencias en los estimados de tiempo, la utilización de las Transformaciones

Seriales y Rápidas de Objetos (TSRO) en lugar de la presentación visual serial y rápida (PVSR) nos evidencia algunos resultados novedosos.

En primer lugar, la discriminación de dos eventos que afectan la misma parte de un objeto es siempre precisa, no importa el tiempo que transcurra entre los eventos. Sin embargo, el cambio de la atención de una parte a otra del mismo objeto demora un tiempo. Lo anterior concuerda con estudios recientes (Vecera, Behrmann y McGoldrick, 2000) que han encontrado que es más fácil discriminar dos atributos de la misma parte de un objeto que de partes distintas de ese mismo objeto. Al mismo tiempo, contradice uno de los principios básicos de los modelos más clásicos de la atención orientada a los objetos, según el cual, una vez que la atención ha seleccionado un objeto, se atiende al objeto como un todo, a todas sus partes y atributos (Kahneman y Henik, 1981). Aún cuando dicho tiempo es relativamente breve al compararse con el tiempo requerido para el cambio de la atención entre objetos, no debemos ignorarlo. Esa demora indica que la atención no se distribuye homogéneamente en todo el objeto atendido. Esto pudiera estar sugiriendo una competencia atencional guiada por la organización perceptual pero que, como la organización misma, se expresa en distintos niveles jerárquicos y no excluyentes.

En segundo lugar, en todas nuestras condiciones experimentales el estatus atencional del objeto donde ocurría el primer evento, y el evento en sí mismo, eran equivalentes. Por otra parte, en los controles experimentales donde la organización perceptual no era ambigua, no siendo necesaria la supresión de uno de los objetos para la percepción clara del otro (por ej.: ambos objetos separados espacialmente en el mismo o en diferentes planos), la supresión disminuyó y los efectos atencionales decayeron. De igual forma, cuando los eventos capturaban automáticamente la atención (por ej.: presentación de un destello), se logró una desinhibición inmediata del objeto no atendido. Sería como si la focalización de la atención sobre un objeto lo convirtiera en figura, suprimiendo al otro objeto convertido en fondo. Por tanto, la demora en el tránsito de la atención del objeto atendido al no atendido no se debe al tiempo durante el cual la atención queda atrapada en el primer objeto, o se encuentra ocupada en el procesamiento del primer estímulo, sino que parece estar más vinculada al grado de supresión del objeto no atendido. De la misma forma que la organización perceptual determina qué se selecciona, es muy probable que también influya en los cambios que se producen en el estatus atencional de los objetos a través del tiempo.

Bases neurales

La técnica de los potenciales relacionados a eventos (PRE) ha sido utilizada como una herramienta para inferir el momento de la selección atencional y sus posibles bases neurales. Si la atención modula la amplitud de los primeros componentes (por ej.: P1 ó P100 y N1 ó N200) de los potenciales provocados por estímulos visuales, se considera que la selección es temprana; si se producen efectos atencionales sobre componentes posteriores (por ej.: P3 y Negatividades de Selección), se estima que la selección es tardía. Al comenzar esta tesis, muchos estudios habían señalado efectos atencionales muy tempranos (pre-perceptuales) cuando la selección se basaba en el espacio (Mangun y Hillyard, 1991; Eimer, 1993; 1994; Luck y cols., 1994; Hillyard y Anllo-Vento, 1998). Estos efectos consistieron en una reducción de la amplitud de los componentes tempranos P1 y N1 provocados por estímulos que se encienden en una localización espacial no atendida. Al mismo tiempo, no se encontró una modulación atencional de estos componentes tempranos cuando la selección se basaba en otros atributos (por ej.: el color), en cuyo caso se producen efectos sobre componentes más tardíos. Estos hallazgos apoyan la idea de que el espacio juega un papel primario en la selección atencional, mientras que otros tipos de selección actúan más tardíamente, en etapas post-perceptuales. Se ha planteado que la base de la atención espacial radica en el control de la información que pasa a las áreas corticales extraestriadas tempranas del sistema visual (Mangun, 1995; Mangun y Hillyard, 1995).

En lugar de eventos que se encienden abruptamente, creando nuevos objetos y capturando automáticamente la atención, nosotros utilizamos breves cambios en la dirección del movimiento. Estos eventos provocan un potencial relacionado con el inicio del movimiento (PR-IM), descrito por varios autores (Göpfert, Muller y Simon, 1990; Kuba y Kubová, 1992a, 1992b; Bach y Ullrich, 1994). Nuestros datos ponen de manifiesto una modulación atencional del componente N1, e incluso una supresión casi absoluta de P1 y N1 para estimulaciones de gran carga perceptual, en un diseño que, como ya hemos visto, excluye la participación de cualquier mecanismo espacial, y evidencia una selección guiada por la organización perceptual de la escena.

A primera vista, pudiera parecer que la modulación atencional de los componentes tempranos encontrada por nosotros pudiera ser algo más tardía que la reportada para la selección espacial, pues la latencia de los componentes modulados (principalmente N1) es algo mayor en nuestros resultados. Sin embargo, es necesario destacar que la latencia de los componentes de un PRE sufre cambios en dependencia de diversos factores relacionados con el estímulo. Se ha reportado que los propios P1 y N1, modulados en los estudios de selección espacial, incrementan notablemente su latencia si se reduce la luminancia o el contraste de los estímulos que los provocan (Kulikowski, 1977; Riggs, 1997).

En el caso particular de los PR-IM, se ha encontrado que la latencia de N1 es menor si los estímulos están estacionarios antes de comenzar a moverse (Göpfert, Muller y Simon, 1990; Kuba y Kubová, 1992a, 1992b; Bach y Ullrich, 1994; Torriente, Valdes-Sosa, Ramirez y Bobes, 1999). Del mismo modo, la latencia se incrementa si ocurre una pre-adaptación al movimiento, originada por un período previo al evento desencadenante, durante el cual el estímulo se encuentre en movimiento (Muller, Göpfert, Breuer, y Greenlee, 1998-1999). Tal es el caso de nuestros experimentos, en los cuales la línea de base crea dicha pre-adaptación. Estos estudios, en conjunto con los controles esperimentales desarrollados en esta tesis, demuestran que los incrementos de latencia de N1 reflejan más que nada diferencias en las condiciones de estimulación.

Por tanto, la latencia relativamente temprana de éste componente, y la ausencia de cambios en su distribución topográfica, lo diferencian claramente de las Negatividades de Selección asociadas a selecciones más tardías basadas en otros atributos elementales (Anllo-Vento y Hillyard, 1996), las cuales sí aparecen en aquellos controles experimentales que imponen una selección atencional de ese tipo (por ej.: basada sólo en el color). La modulación atencional temprana de los potenciales provocados por los eventos que ocurren en una superficie no atendida, asociada a la disminución en la capacidad de detectar dichos eventos (d'), apuntan hacia una selección que opera en los estadios preperceptuales, descontaminada de los procesos decisorios más tardíos.

No obstante, la comparación decisiva entre ambos tipos de componentes y los mecanismos que ellos reflejan, es al nivel de sus generadores neurales, los cuales, desafortunadamente, aún no han sido determinados inequívocamente. El componente N1, provocado por la aparición abrupta de estímulos, consta de tres subcomponentes localizados en las áreas frontal, occípito-parietal y occípito-temporal (Clark, Fan y Hillyard, 1995; Johannes, Munte, Heinze, y Mangun, 1996). Los dos últimos son modulados por la atención, y parecen generarse en las áreas extraestriadas tempranas de la corteza visual, incluyendo el área V4 en la vía ventral (Clark y Hillyard, 1996).

Se estima que la fuente generadora de un campo magnético relacionado con el inicio del movimiento (equivalente, en principio, a la N1 estudiada aquí) se localiza en la corteza occipito-temporal, en un área que es considerada como el homólogo en el hombre de MT/MST, en la vía dorsal (Anderson, Holliday, Singh y Harding, 1996; Patzwahl, Elbert, Zanker y Altenmüller, 1996). Por tanto, las bases neurales de estos dos tipos de N1 probablemente estén ambas localizadas en áreas extraestriadas tempranas de la corteza visual, pero posean generadores propios.

En resumen, tanto la atención espacial como la orientada a objetos modulan componentes tempranos similares, lo cual sugiere que reflejan los mismos mecanismos atencionales tempranos, en lugar de actuar en etapas sucesivas de la percepción. Otras evidencias proponen, congruentemente, que las propiedades de las superficies y los objetos se reflejan en las cortezas visuales más tempranas (Verghese y Stone, 1996), incluyendo V4 (Schein y Desimone, 1990), MT (Allman, Miezin y McGuinness, 1985), V2 (Peterhans y von der Heydt, 1989) e incluso V1 (Knierim y Van Essen, 1992; Singer, 1993; Lamme, 1995; Rossi, Rittenhouse y Paradiso, 1996). Se echa por tierra así el supuesto privilegio otorgado a la selección espacial, como la única que ocurre en las áreas corticales extraestriadas tempranas del sistema visual.

Conclusiones y recomendaciones

Conclusiones

1. La segmentación de una escena en objetos influye sobre la atención selectiva a eventos que los transforman, al menos en condiciones que exluyen la participación de mecanismos alternativos, tanto espaciales como de filtraje sensorial de bajo nivel.
2. El tiempo mínimo para poder procesar dos eventos sin interferencia es mayor (al menos 100 milisegundos) cuando la atención debe cambiar de una parte a otra de un objeto que cuando la atención se mantiene en una misma parte del objeto. La distribución de la atención dentro del mismo objeto no es homogénea.
3. El tiempo mínimo para poder procesar dos eventos sin interferencia es mucho mayor (alrededor de medio segundo) cuando la atención debe cambiar de un objeto a otro que cuando la atención se mantiene dentro del mismo objeto, aún si en este último caso la atención debe desplazarse de un sitio espacial a otro. La supresión relativa de la representación de un objeto es una limitante considerable al tránsito de la atención entre objetos. Esta demora del tránsito atencional entre objetos no está sujeta al control voluntario del sujeto.
4. El control de la atención dirigida hacia eventos que modifican objetos, a pesar de estar influido por la organización perceptual de la escena, ocurre en etapas muy tempranas del procesamiento visual, operando como un mecanismo de control de ganancia en las cortezas extraestriadas.
5. La atención a eventos que no están integrados a la organización perceptual de la escena no está sujeta a la influencia de esta última, dependiendo estrictamente de factores espaciales. Lo mismo sucede con los eventos que capturan automáticamente la atención. Por tanto, el tipo de estímulos normalmente utilizados en la técnica de PRE podría entonces explicar la escasez de estudios psicofisiológicos basados en dicha técnica que demuestren exitosamente la atención a objetos.

Recomendaciones

1. Realizar estudios de Potenciales Relacionados a Eventos con nuestro diseño de figuras, y compararlos con los resultados obtenidos con las superficies transparentes, para profundizar en el conocimiento de la importancia relativa de las vías visuales dorsal y ventral en la selección atencional.
2. Empleando la Tomografía Eléctrica Cerebral, localizar los generadores neurales de los potenciales descritos en este trabajo y recomendados en el punto anterior, para confirmar el papel de las áreas corticales visuales extraestriadas.
3. Realizar estudios utilizando las Imágenes de Resonancia Magnética Funcional, para precisar las áreas corticales implicadas en la atención a eventos orientada a los objetos.
4. Extender los diseños utilizados a estudios con microelectrodos en monos, con el objetivo de conocer cómo opera la supresión de objetos a nivel neuronal.
5. Realizar estudios con pacientes para determinar el papel de la organización perceptual en los síndromes con alteraciones de la atención visual (hemi-inatención, extinción, simultagnosia).

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