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Estimation de la numérosité, de la durée et de la longueur au sein du cortex pariétal

Investigations comportementales et en neuroimagerie

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A ma grand-mère.

"On peut tromper une fois mille personnes. On peut tromper mille fois une personne. Mais on ne peut pas tromper mille fois, mille personnes…"

"- Parlez-moi de vous plutôt.

- Odile, moi c'est Odile… Pluto c'est l'ami de Mickey.

- Ah non, Pluto c'est le chien de Mickey… L'ami de Mickey c'est Dingo!

- Oh pardonnez-moi, je ne sais plus ce que je dis… C'est ce film, toute cette pression…"

Dialogues du film "La Cité de la peur"

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Introduction Générale

La perception de l'espace, du temps et des quantités correspond à des processus cognitifs extrêmement importants, utilisés constamment tant par l'animal que par l'être humain. Au quotidien, l'homme doit évaluer ces paramètres afin de sélectionner et de produire des comportements adéquats au sein de son environnement. Ces habiletés se développent précocement au cours de l'ontogenèse et sont également observables chez certaines espèces animales. Nombres et espace sont depuis très longtemps associés, que ce soit par les philosophes du début du 20ème siècle (Bergson, 1911; Wertheimer, 1912) ou à travers de nombreux concepts mathématiques et physiques (e.g., ligne droite, coordonnées cartésiennes, plan, etc.). Les premiers indices d'interférence de la longueur sur le jugement d'équivalence numérique ont été apportés par les études piagétiennes chez les jeunes enfants (Piaget & Szeminska, 1941): ceux-ci étaient en effet incapables de reconnaitre que deux rangées de longueurs différentes pouvaient contenir un nombre identique de jetons. L'idée que les grandeurs numériques puissent être représentées spatialement est aujourd'hui largement acceptée et forme la base des recherches sur les aspects spatiaux du traitement numérique (Dehaene, 1997). Les liens entre le domaine numérique et temporel d'une part, et entre l'espace et le temps, d'autre part, sont plus rarement abordés. Toutefois, des liens entre la perception des nombres et du temps ont été rapportés dès les années 1890 (Walsh & Pascual-Leone, 2003) et des preuves reliant ces trois dimensions peuvent être trouvées notamment dans la littérature neurologique. La présence simultanée de déficits dans le traitement du temps, de l'espace et des nombres a en effet été décrite pour la première fois chez des patients présentant une atteinte sélective du cortex pariétal (Critchley, 1953).

A partir de travaux réalisés sur des rats, Meck et Church (1983) ont été les premiers à postuler l'existence d'un système spécifique et commun, sollicité tant par l'estimation de la numérosité que de la durée et permettant de représenter ces deux dimensions de manière similaire. En effet, au cours de leurs expériences, la capacité des rats à traiter de façon

indifférenciée la numérosité ou la durée lorsque ces deux dimensions covariaient dans des séquences d'événements a été mise en évidence. Depuis le modèle de l'accumulateur de Meck et Church (1983), la question de l'existence de représentations distinctes ou communes pour différents types de dimensions quantifiables suscite un regain d'intérêt. Récemment, Walsh (2003) a proposé l'existence d'un système de magnitude généralisée (*A theory of Magnitude*, ATOM) localisé au niveau du cortex pariétal inférieur et sous-tendant la représentation de l'espace, du temps et la quantité numérique à partir d'un système métrique commun. Si de nombreuses études extraites de trois littératures spécifiques et distinctement séparées semblent appuyer favorablement cette théorie ATOM, peu de recherches ont investigué les liens fonctionnels et neuroanatomiques directs pouvant exister entre ces divers traitements cognitifs.

Ceci constitue le principal objectif de notre thèse, à savoir, dégager les interactions fonctionnelles ainsi que la spécificité et/ou la communauté des substrats neuroanatomiques des mécanismes de traitement de la numérosité, du temps et de la longueur. L'étude des processus d'estimation de magnitude sera ici focalisée sur l'exploration des capacités de discrimination de numérosité, de durée et de longueur chez le participant adulte sain. Notre exposé sera subdivisé en trois parties distinctes. La première partie, correspondant au chapitre 1, se centrera sur le contexte théorique de la problématique. Ainsi, ce chapitre abordera les similitudes et dissemblances pouvant être observées entre les processus d'estimation de la numérosité, de la durée et de la longueur. En effet, l'exploration spécifique de chacune de ces magnitudes, que ce soit au niveau comportemental, neurophysiologique ou encore neuroanatomique, a largement été développée ces dernières décennies et a donné lieu à des résultats majoritairement convergents. Une seconde partie de ce premier chapitre se focalisera sur les liens existants entre les différents processus d'estimation de magnitude, en rendant compte des interactions comportementales observées lors du traitement simultané de plusieurs dimensions, ainsi que des

populations neuronales activées de façon commune dans plusieurs processus d'estimation tant chez le singe que chez l'être humain.

La seconde partie, constituée des chapitres 2 à 9, décrira la contribution expérimentale de ce travail, qui a pour objectif principal de préciser d'une part les interactions comportementales existant entre les processus d'estimation de numérosité, de durée et de longueur et d'autre part de mettre en évidence la spécificité et/ou communauté des substrats neuroanatomiques de ces trois processus. En combinant les approches comportementales et neurofonctionnelles, cette partie aura donc pour visée d'apporter des éléments permettant de répondre aux interrogations suivantes: (1) Quelles sont les interactions comportementales existant entre les différents processus d'estimation de magnitude et dans quelle mesure des dimensions non directement pertinentes pour la tâche requise peuvent-elles interférer avec le jugement d'une dimension déterminée ? (2) Existe-t-il des zones cérébrales impliquées communément dans les processus d'estimation de numérosité, de durée et de longueur ? (3) Est-ce que les zones cérébrales bordant le sillon intrapariétal (SIP), correspondant à une région nécessaire au traitement de la numérosité comme démontré dans de récentes études en SMT (voir chapitre 1, point 2.3.3), sont également impliquées de façon cruciale dans d'autres processus d'estimation comme le traitement de la durée ou encore de la longueur ?

Enfin, la troisième et dernière partie de cette thèse, à savoir le chapitre 10, sera consacrée d'une part à la proposition d'une synthèse générale des résultats obtenus dans le cadre de ce travail, et d'autre part à une mise en perspective desdits résultats. Les principales implications théoriques de nos recherches, tant aux plans comportemental que neuroanatomique, seront ainsi présentées, de même que leurs principales limites et que certaines propositions quant aux directions que pourront prendre les recherches futures dans l'exploration des divers processus d'estimation de magnitude.

Chapitre 1

Processus d'estimation de la numérosité, de la durée et de la longueur

1. Modèles théoriques

Les capacités de discrimination de numérosités, de durées et de longueurs sont observables tant chez l'animal que chez l'homme et celles-ci se manifestent de façon précoce au cours de l'ontogenèse. Dans ce chapitre, deux modèles théoriques distincts ayant postulé d'une part, à un niveau fonctionnel, une association spécifique entre l'estimation de la numérosité et de la durée et, d'autre part, à un niveau anatomique, l'existence d'un système de magnitude généralisée situé au niveau du cortex pariétal, vont être développés.

Suite à des travaux réalisés sur des rats, le modèle de l'accumulateur (Meck & Church, 1983) a été le premier à rendre compte d'un mécanisme interne sollicité tant par l'estimation de la numérosité que de la durée et permettant de représenter ces deux dimensions de manière similaire. Dans une première expérience, ces chercheurs ont tout d'abord entraîné des rats à discriminer des séquences de sons sur base de leur numérosité ou de leur durée totale. Deux séquences ont été utilisées au cours de l'entraînement: l'une comprenait deux sons et durait deux secondes, l'autre comprenait huit sons et durait huit secondes. Les rats ont appris à répondre à chacune des deux séquences en appuyant sur le levier correspondant (levier de gauche et levier de droite, respectivement). Ensuite, dans la partie expérimentale, des séquences de sons non entraînées ont été présentées en plus des séquences utilisées au cours de l'entraînement alors que les animaux devaient répondre selon les mêmes critères qu'à l'entraînement. Contrairement aux séquences entraînées pour lesquelles les dimensions temporelles et numériques étaient confondues, les séquences de sons non entraînées ont été construites en maintenant une des deux dimensions fixe tout en faisant varier l'autre. Dans la condition de discrimination de numérosités, le nombre de sons variait de deux à huit (2, 3, 4, 5, 6 ou 8 sons) alors que la durée totale des séquences était maintenue à quatre secondes. Dans la condition de discrimination de durées, la durée totale des séquences variait de deux à huit secondes (2, 3, 4, 5, 6 ou 8 sec) tandis que le nombre de sons était maintenu à quatre. Les rats se sont montrés aptes à généraliser les

associations apprises au cours de l'entraînement et, ainsi, à discriminer les différentes séquences sur base de leur durée totale ou du nombre de sons qu'elles comportaient. Par exemple, dans la condition d'estimation de durées, une séquence de deux secondes (quatre sons) était associée avec le levier de gauche alors qu'une séquence de huit secondes (quatre sons) était associée avec le levier de droite. De manière intéressante, les auteurs ont mis en évidence que les fonctions psychophysiques des réponses pour la discrimination des séquences sur base de la durée d'une part, et de la numérosité d'autre part, étaient superposables. Au cours d'une seconde expérience, de la métamphétamine a été administrée aux rats. Cette substance a eu pour effet d'affecter leurs performances de manière analogue dans la discrimination tant de la durée des séquences que du nombre de sons qu'elles comportaient. En effet, les fonctions psychophysiques de réponses pour la discrimination de durées et de numérosités se sont décalées de 10% vers la gauche. Autrement dit, les durées et les numérosités perçues ont été surestimées avec la même amplitude suite à l'administration de métamphétamine. Enfin, au cours d'une troisième expérience, les rats se sont montrés capables de transférer la perception de la numérosité et de la durée des séquences de sons à des séquences de stimulation cutanées. Sur base de ces observations, Meck et Church ont émis l'hypothèse selon laquelle l'estimation de la numérosité et l'estimation de la durée solliciteraient un mécanisme interne commun, correspondant à un accumulateur permettant de représenter ces deux dimensions de manière analogue à partir de modes opératoires différents.

En s'inspirant du modèle de traitement de l'information temporelle de Gibbon (1977) et en l'élargissant au domaine numérique, le modèle de l'accumulateur ainsi proposé repose sur trois étapes successives (Figure 1.1A). Au cours de la première étape, un générateur interne, correspondant à une horloge ou à un compteur, libère des impulsions à intervalles réguliers vers un accumulateur au sein duquel ces impulsions sont sommées. La transmission des impulsions est par ailleurs régulée par un interrupteur, situé entre le générateur d'impulsions et l'accumulateur,

et fonctionnant selon différents modes opératoires. Ainsi, lorsque l'interrupteur est en mode "continu", le stimulus initial engendre une impulsion qui se maintient jusqu'à la fin de l'intervalle. Lorsque l'interrupteur est en mode "stop", une impulsion est libérée à chaque stimulation pendant un temps variable, correspondant à la durée de la stimulation. Ces deux premiers modes permettent de représenter la durée d'intervalles de temps. Un troisième mode, dit "événement", est utilisé pour l'estimation de grandeurs numériques. Dans ce dernier cas, chaque apparition d'un stimulus déclenche une impulsion de durée fixe, indépendamment de la durée du stimulus. Selon le mode opératoire sélectionné, l'ensemble des stimulations ainsi sommées dans l'accumulateur représente soit la durée soit la numérosité estimée. Au cours d'une seconde étape, les impulsions sommées dans l'accumulateur sont stockées pendant une brève période de temps en mémoire de travail et comparées aux informations temporelles préalablement stockées en mémoire de référence. La troisième étape correspond à la prise de décision. Au cours de cette étape, la réponse la plus adéquate est sélectionnée sur base de la comparaison entre la représentation de la valeur de l'accumulateur, activée temporairement en mémoire de travail, et les représentations stockées en mémoire de référence. Ce modèle sous-tend ainsi les processus d'estimation de grandeurs numériques et d'intervalles de temps chez l'animal. Son fonctionnement n'est néanmoins pas infaillible et la précision avec laquelle la valeur de l'accumulateur est représentée en mémoire de travail obéit à la loi de Weber. Ainsi, la précision de l'accumulateur décroît avec l'augmentation de la magnitude à estimer. Enfin, les ressources attentionnelles peuvent influencer chacune des étapes de ce processus et altérer la précision des performances du sujet dans l'estimation des propriétés temporelles ou numériques d'un stimulus.

Les premiers modèles d'encodage de la quantité numérique dérivent directement du modèle de l'accumulateur. Ainsi, les processus itératifs et discrets impliqués dans ce modèle incarneraient les principes du comptage selon le modèle sériel du dénombrement préverbal de Gallistel et Gelman (1992). Une représentation analogique et approximative de la quantité très

proche de celle de l'accumulateur est également postulée dans le modèle des détecteurs de numérosité (Dehaene & Changeux, 1993) et correspondrait à la représentation sémantique du nombre utilisée par l'adulte.

Si ce modèle a permis de rendre compte d'un grand nombre de données récoltées tant chez l'animal que chez l'humain, en suggérant l'existence d'un seul accumulateur ne pouvant traiter les informations de numérosité et de durée qu'une catégorie à la fois, il présente deux limites importantes. Tout d'abord, ce modèle ne peut expliquer la présence éventuelle d'une dissociation entre le traitement de la numérosité et de la durée, un déficit de l'accumulateur entrainant nécessairement une perturbation équivalente dans les deux traitements. De plus, aucune interaction comportementale entre les dimensions numériques et temporelles ne devrait être observée, les deux traitements ne pouvant avoir lieu simultanément. Or, comme les pages suivantes le décriront, une dissociation entre les processus d'estimation de la numérosité et de la durée a été observée chez un patient présentant des performances déficitaires dans une tâche de durée alors qu'aucun déficit n'était relevé dans une tâche d'estimation de numérosité (voir point 3.3.1). En outre, des effets d'interférences entre ces deux dimensions ont été décrits à plusieurs reprises dans la littérature (voir point 3.1). Ces données ne sont donc pas compatibles avec le modèle de l'accumulateur et déforcent quelque peu la portée de celui-ci.

Depuis le modèle de l'accumulateur de Meck & Church (1983), la question de l'existence de représentations distinctes ou communes pour différents types de dimensions quantifiables suscite un regain d'intérêt. Récemment, en accord avec l'idée développée par Gallistel et Gelman (2000) que toutes les quantités discrètes et continues devraient être représentées à partir de magnitudes mentales semblables, étant donné que dans de nombreuses situations plusieurs types de quantités peuvent être combinées afin d'orienter d'importantes décisions comportementales, Walsh (2003) a postulé l'existence d'un système de magnitude généralisée. Celui-ci serait localisé au niveau du cortex pariétal inférieur et sous-tendrait la représentation de

l'espace, du temps et de la quantité numérique à partir d'un système métrique commun (Figure 1.1B).

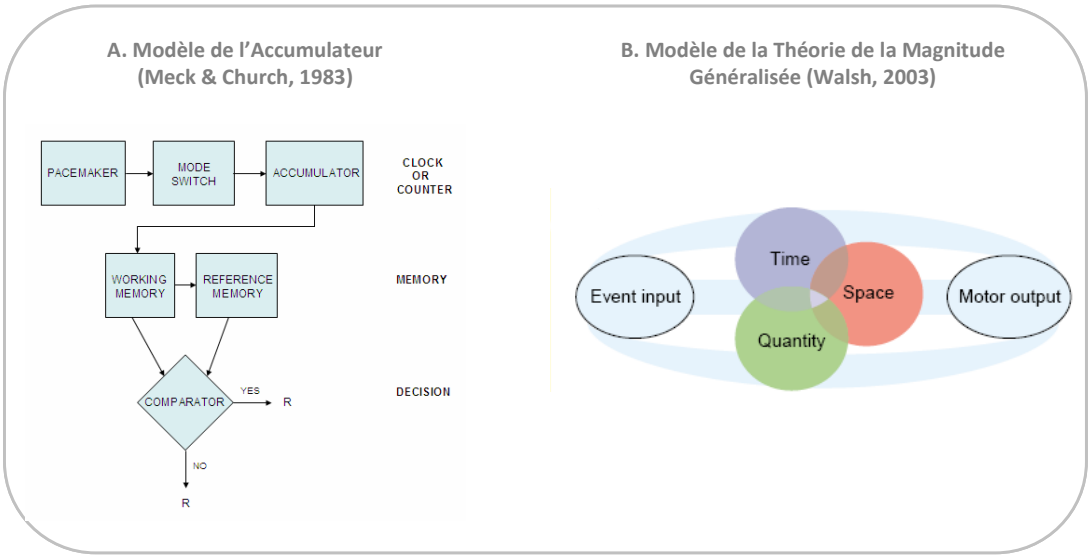

Figure 1.1: Représentation schématique (A) du système de traitement des dimensions numériques et temporelles selon le modèle de l'accumulateur de Meck et Church (1983) et (B) du système de magnitude généralisée (Walsh, 2003). (A) Le modèle de l'accumulateur sous-tend les processus d'estimation de la numérosité et de la durée chez l'animal et leur octroie un mécanisme de fonctionnement commun. Il est composé de trois étapes distinctes: l'accumulation, le maintien en mémoire de travail et la prise de décision. (B) Le modèle de la magnitude généralisée postule quant à lui que le traitement du temps, de l'espace et des quantités numériques reposeraient sur un système métrique commun.

De plus, le traitement des magnitudes partagerait un système métrique orienté vers l'action. En effet, selon ce modèle, le traitement des magnitudes dépendrait d'un algorithme développemental pour des distinctions du type "plus que - moins que", distinctions applicables à tout élément du monde externe. Cet algorithme serait situé au niveau du cortex pariétal et se développerait par l'interaction de l'humain avec son environnement, à travers la sélection d'actions sensori-motrices (Figure 1.1B). Par conséquent, il serait fortement lié aux comportements moteurs, ce qui pourrait expliquer sa localisation sur la voie dorsale, impliquée dans l'action. Par ailleurs, le système de magnitude généralisée serait présent dès la naissance et se développerait progressivement (voir encadré 2 pour plus de détails). Enfin, en ce qui concerne

l'estimation de la durée et de la numérosité, elles reposeraient sur des principes d'accumulation similaires, tels qu'ils ont été postulés dans le modèle de l'accumulateur.

Si cette proposition de modèle apparait intuitivement intéressante et semble en accord avec une grande majorité des résultats comportementaux et neuroanatomiques observés ces dernières années, comme cela sera décrit dans les parties qui vont suivre, elle reste toutefois à ce stade sous-spécifiée, ne rendant compte majoritairement que de données obtenues grâce à l'exploration d'une seule dimension à la fois et ne définissant que de façon approximative la nature et l'étendue des magnitudes pouvant être concernées par ce système généralisé. De plus, aucune prédiction claire n'est formulée concernant les relations entre les différentes magnitudes et peu d'informations sont disponibles sur les mécanismes et les corrélats cérébraux spécifiques à chaque dimension ou partagés par plusieurs d'entre elles.

En revisitant ATOM à la lumière des récentes études explorant les processus d'estimation de magnitude, certaines prédictions de cette théorie ont été complétées et précisées (Bueti & Walsh, 2009). Ainsi, les raisons ontogénétiques du développement d'un système généralisé plus particulièrement dans le cortex pariétal vont être davantage soulignées. L'enfant serait en effet doté d'un système général d'appréhension des quantités situé au niveau du cortex pariétal, sur les bases duquel se développeraient par la suite les habiletés numériques discrètes. Cette version tente également de justifier l'utilisation d'un système métrique commun en dehors d'un contexte lié à l'action et de rendre compte des effets d'interférence asymétriques rencontrés dans certaines études. Enfin, le cortex pariétal est pointé comme étant un des centres du traitement de la magnitude, faisant partie d'un système plus vaste. Le cortex préfrontal semblerait également impliqué dans ce système. Plusieurs questions restent toutefois toujours sans réponse. Par exemple, les opérations spécifiques sous-tendues par la représentation de la magnitude, ou encore le rôle distinct de chaque hémisphère restent encore nébuleux.

L'argumentation développée par le modèle ATOM repose sur une large revue de données comportementales, développementales, physiologiques, lésionnelles et neuroanatomiques issues de trois littératures séparées sur le traitement de l'espace, du temps et de la numérosité. Ces données vont être synthétisées et complétées dans les pages qui suivent, en insistant particulièrement sur les similarités et les dissemblances observées entre ces trois processus d'estimation de la magnitude. Les travaux abordant de façon directe les interactions, tant fonctionnelles que neuroanatomiques, entre différentes dimensions seront ensuite largement décrits. Enfin, les questions laissées en suspens à ce stade par le modèle ATOM seront abordées et les principaux objectifs testés dans notre partie expérimentale présentés.

Encadré 1. Terminologie & Définitions

Il parait important de définir ici quelques concepts utilisés tout au long de cette thèse et d'également cibler l'étendue précise des dimensions étudiées au cours de ce travail. Ces dimensions que sont la numérosité, l'espace et le temps recouvrent toutes trois un vaste domaine impliquant des processus cognitifs divers et spécifiques.

Tout d'abord, en ce qui concerne la **dimension numérique**, la **quantification** correspond à un processus par lequel la numérosité d'une collection est extraite et la représentation mentale correspondante activée. Trois processus distincts de quantification ont été mis en évidence (Mandler & Shebo, 1982): le subitizing, le dénombrement et l'estimation. Dans le cadre de cette thèse, seules les études investiguant les processus d'estimation de la numérosité non-symbolique seront développées. L'**estimation** est définie comme étant un processus approximatif et rapide permettant la quantification de collections d'éléments lorsque la **numérosité** de la collection à quantifier est trop importante ou que le temps dont on dispose est insuffisant que pour avoir recours au dénombrement.

Le **temps** est une notion complexe et vaste qui recouvre différentes échelles temporelles. Sur base des comportements associés et des mécanismes neuronaux sous-jacents, quatre échelles ont été distinguées (Mauk & Buonomano, 2004) : microsecondes, millisecondes, secondes ou durées brèves et rythme circadien. Au cours de cette thèse, notre intérêt portera principalement sur les études ayant investigué les processus d'**estimation** de **durées brèves** (i.e., autour de la seconde). Cette catégorie temporelle représente en effet des durées suffisamment brèves pour éviter la possibilité de mise en place de stratégies de comptage. De plus, le traitement de ce type de durées implique des zones corticales.

Enfin, la **dimension spatiale** réfère elle aussi à des traitements cognitifs très diversifiés, incluant par exemple la rotation mentale, l'attention spatiale, la planification oculomotrice, ou encore la perception de l'espace proche et lointain. Si Walsh reste imprécis en définissant l'espace comme "toute information spatiale utilisée pour l'action" (p.483, 2003), l'estimation de la longueur dans le sens auquel cette thèse l'entend, renvoie à l'**estimation explicite de longueur** de stimuli présentés dans le champ visuel proche.

2. Similitudes et dissemblances entre les processus d'estimation de magnitude

2.1 Données comportementales

De nombreux parallélismes peuvent être évoqués au niveau des performances comportementales observées au cours de tâches de discrimination de durée, de numérosité ou de longueur. Premièrement, l'ensemble de ces processus perceptifs obéissent à la loi de Weber[1], selon laquelle l'accroissement de l'intensité d'un stimulus nécessaire pour produire un accroissement perceptible de la grandeur de la sensation est une fonction constante de l'intensité de ce stimulus. Deuxièmement, signatures comportementales typiquement rencontrées dans le jugement numérique (Moyer & Landauer, 1967), les effets de distance et de taille ne sont pas exclusivement observés lors du traitement de cette dimension, mais se retrouvent également lors de comparaison d'autres magnitudes (Tableau 1.1). L'effet de distance renvoie à l'observation que l'aptitude à discriminer deux nombres augmente lorsque la distance qui les sépare s'accroit. L'effet de taille, qui reflète la loi de Weber, se réfère au fait qu'à distance numérique égale, la discrimination de deux nombres diminue lorsque leur taille numérique augmente. Ces effets sont donc présents pour tous les jugements de dimensions psychophysiques quantifiables, comme la longueur de lignes (e.g., Fias, Lammertyn, Reynvoet, Dupont & Orban, 2003; Henmon, 1906; Johnson, 1939), la durée de séquences (e.g., Droit-Volet, Tourret & Wearden, 2004), ou encore la taille physique de formes géométriques (e.g., Fullbright, Manson, Skudlarski, Lacadie & Gore, 2003) ou de symboles numériques (e.g., Cohen Kadosh et al., 2005; Kaufmann et al., 2005; Pinel, Piazza, Le Bihan & Dehaene, 2004; Tang et al., 2006)[2].

[1] Loi de Weber: $\Delta I/I=k$, où I correspond à l'intensité du stimulus et k est une constante.

[2] Notons qu'un effet de distance a également été observé dans des tâches de jugement de tonalités (Henmon, 1906; Rusconi , Kwan, Giordano, Umilta & Butterowrth, 2006) et de luminosité (Cohen Kadosh et al., 2005; Cohen Kadosh & Henik, 2006; Pinel et al. 2004) mais aussi dans des tâches de comparaison de statut social (Chiao, Bordeaux & Ambady, 2004), de lettres de l'alphabet (Hamilton & Sanford, 1978; Lovelace & Snodgrass, 1971) et de férocité d'animaux (Thioux, Pesenti, Costes, De Volder & Seron, 2005).

Tableau 1.1: Synthèse des études comportementales menées sur des adultes rapportant un effet de distance et/ou de taille dans des tâches de comparaison de diverses magnitudes (adapté en partie de Cohen Kadosh, Lammertyn & Izard, 2008 et de Pesenti, 1995).

Dimensions	Stimuli	Effets	Auteurs
Numérosité	Ensembles de points	Distance & Taille	Buckley & Gillman (1974)
Longueur & Taille	Lignes Formes géométriques Chiffres arabes	Distance & Taille	Birren & Botwinick (1955), Cohen Kadosh et al. (2005), Cohen Kadosh & Henik (2006), Fias et al. (2003), Fullbright et al. (2003), Henmon (1906), Johnson (1939), Kaufmann et al. (2005), Moyer & Bayer (1976), Paivio (1975), Pinel et al. (2004), Tang et al. (2006)
Durée	Durée de séquences	Distance	Droit-Volet et al., (2004), Holyoak & Walter (1976)

Enfin, une autre similarité entre ces différents processus d'estimation se marque dans les données développementales et dans la trajectoire évolutive de la construction de ces représentations. L'investigation précise des capacités de discrimination de magnitude chez des bébés âgés de quelques mois par l'utilisation de paradigmes d'habituation comparables converge en effet vers des résultats semblables quelle que soit la dimension étudiée (Figure 1.2). Ainsi, il apparait que le profil de performances de ces bébés sont identiques pour la discrimination de durées, de surfaces et de numérosités (respectivement, van Marle & Wynn, 2006; Brannon, Lutz & Cordes, 2006; Xu & Spelke, 2000; pour une revue, voir Feigenson, 2007). Dans ces trois études, des bébés âgés de six mois réagissent à un changement de numérosité, de surface et de durée quand le rapport entre les deux stimuli est de 1:2 mais échouent dans la détection de ce changement lorsque le rapport est de 2:3. De plus, la progression des enfants dans leur capacité à discriminer les durées et les numérosités est semblable puisque des enfants âgés de 10 mois parviennent à détecter des changements avec des stimuli dont le rapport est de 2:3 (Brannon, Suanda & Libertus, 2007; Lipton & Spelke, 2003).

Enfin, en accord avec les résultats de ces études, la comparaison de la trajectoire développementale de l'effet de distance dans des tâches de comparaison de quantités

numériques symboliques et non symboliques, de tailles ou de luminosités chez de jeunes enfants démontre un décroissement similaire de cet effet proportionnel à l'augmentation de l'âge des participants pour tous les types de comparaison testés (Holloway & Ansari, 2008).

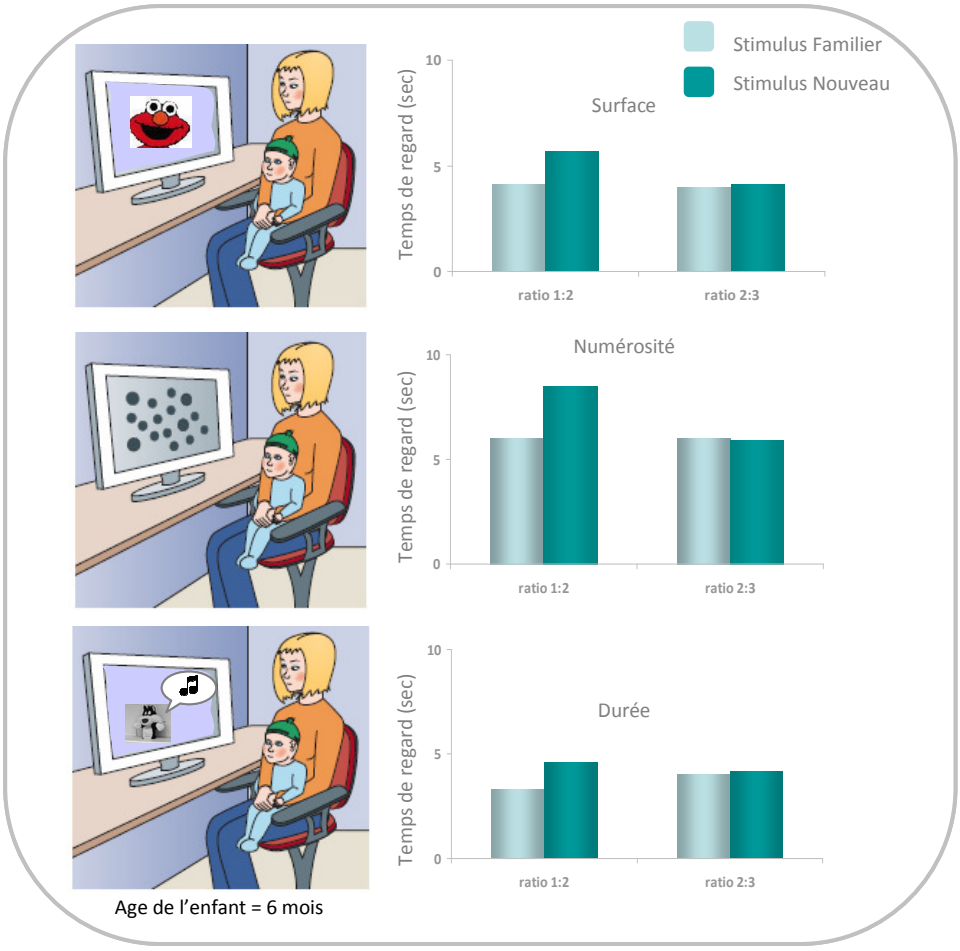

Figure 1.2: Convergence dans la précision des représentations de magnitude à travers différentes dimensions chez le jeune enfant. Les graphiques illustrent les préférences de regard des bébés âgés de 6 mois envers des stimuli nouveaux par rapport aux stimuli familiers pour la surface (adapté de Brannon et al., 2006), la numérosité (adapté de Xu & Spelke, 2000) et la durée (adapté de vanMarle & Wynn, 2006). Pour les trois dimensions, les enfants sont capables de discriminer les magnitudes d'un ratio de 1:2, alors qu'ils n'y parviennent pas pour un ratio de 2:3 (représentations de gauche adaptées de Ansari, 2008).

Néanmoins, quelques dissemblances entre ces traitements ont également été mises en évidence, notamment la présence d'une dissociation fonctionnelle entre les dimensions discrètes et continues quant aux opérations pouvant être réalisée sur celles-ci. Des enfants âgés de 9 mois sont en effet capables d'additionner des numérosités (Mc Crink & Wynn, 2004; Wynn, 1992),

alors qu'ils ne parviennent pas à réaliser des opérations similaires à partir de magnitudes continues comme des volumes (Huntley-Fenner, Carey & Solimando, 2002).

L'ensemble de ces observations laisse suggérer l'existence d'une représentation commune des magnitudes. Toutefois, la présence d'effets comportementaux homologues dans le traitement des dimensions numériques et non numériques ainsi que les similitudes dans l'acquisition de ces habiletés cognitives au cours du développement n'impliquent pas nécessairement le partage d'une seule et même représentation. En effet, des stimuli supportant des fonctions de réponses similaires peuvent être, théoriquement, traités par des mécanismes distincts (Rumelhart & Mc Clelland, 1986). Les effets de taille et de distance peuvent être des patterns comportementaux observés avec des magnitudes différentes sans pour autant qu'une représentation commune en soit à l'origine, ces effets pouvant émerger au niveau d'une étape intermédiaire entre l'accès aux représentations et la prise de décision (Cohen Kadosh, Tzelgov & Henik, 2008; Verguts, Fias & Stevens, 2005). Les données développementales peuvent également être la conséquence d'un mécanisme de comparaison ou de traitement partagé par plusieurs représentations de magnitude distinctes. A ce stade, des preuves supplémentaires sont donc nécessaires pour parvenir à une réelle distinction et pouvoir déterminer à quel niveau la convergence entre les dimensions a lieu. D'une part, les études investiguant les effets d'interférence mutuelle entre les dimensions dans divers paradigmes comportementaux pourraient fournir des preuves plus convaincantes (voir point 3.1). D'autre part, plus fondamentalement, les données comportementales seules semblent insuffisantes pour répondre clairement à cette distinction. Une voie complémentaire afin d'investiguer cette proposition de représentations distinctes *vs.* partagées consiste à explorer les substrats neuronaux sous-tendant les processus d'estimation de magnitude. Ces études feront l'objet des paragraphes qui vont suivre, les données d'enregistrement neuronal chez le singe étant présentées en premier lieu, suivies par les études neuropsychologiques et neuroanatomiques chez l'humain.

2.2 Données neurophysiologiques chez le singe

Comparativement à l'imagerie cérébrale fonctionnelle chez l'être humain, l'enregistrement cellulaire chez l'animal est une technique présentant de nombreux avantages tant au niveau de la résolution spatiale que temporelle et permettant d'analyser l'activité cérébrale à l'échelle du neurone. De récentes études ont ainsi enrichi considérablement les connaissances relatives d'une part, aux régions cérébrales sous-jacentes à l'estimation de différentes magnitudes (e.g., numérosité, durée, proportion) et, d'autre part, à la manière dont ces informations sont représentées au niveau neuronal dans ces régions.

Des neurones sensibles à la numérosité ont été initialement enregistrés dans les régions pariétales chez le chat (Thompson, Mayers, Robertson & Patterson, 1970). Plus récemment, l'enregistrement cellulaire chez le primate a permis d'identifier des neurones dans les régions pariétales et préfrontales au cours de tâches sensori-motrice (Sawamura, Shima & Tanji, 2002) ou d'appariement de collections de points présentées visuellement (Nieder, Freedman & Miller, 2002; Nieder & Miller, 2004; Roitman, Brannon & Pratt, 2007; Figure 1.3A). Comme illustré dans la figure 1.3D, les neurones répondant sélectivement à la numérosité sont abondants dans le cortex préfrontal dorsolatéral et dans une partie profonde du SIP, l'aire ventrale intrapariétale (VIP; Colby, Duhamel & Goldberg, 1993). Ces neurones répondent à des valeurs numériques spécifiques indépendamment des attributs non numériques des stimuli. Ils déchargent de manière maximale pour une numérosité préférentielle mais également suite à la présentation d'une valeur numérique proche, l'activité diminuant parallèlement avec l'augmentation de la distance numérique par rapport à la numérosité préférentielle (les deux graphiques de la figure 1.3A représentent cette diffusion d'activation autour de la valeur cible). De plus, les profils d'activité de ces neurones corrèlent avec les performances comportementales des singes puisqu'ils répondent à la loi de Weber, c'est-à-dire que la précision de la représentation numérique décroit de façon linéaire avec l'augmentation de la numérosité préférentielle (Nieder

& Miller, 2003). D'autres neurones, enregistrés dans une région plus latérale et postérieure du sillon intrapariétal (LIP), répondent également à la numérosité mais déchargent de façon monotone (i.e., en augmentant ou diminuant avec le logarithme de la numérosité de l'ensemble présenté, sans être liés à une numérosité particulière) et possèdent des champs récepteurs limités, ne répondant qu'à la numérosité du sous-ensemble d'éléments apparaissant dans une région rétinotopique bien délimitée (Roitman et al., 2007). Ces auteurs ont suggéré que ces deux types de codage neuronal répondant à la numérosité (lié à une numérosité *vs.* proportionnel à la numérosité) pourraient refléter les deux étapes distinctes de l'extraction de la numérosité proposées dans les modèles neuronaux computationnels de la représentation numérique (Dehaene & Changeux, 1993; Verguts & Fias, 2004). Le codage monotone de la magnitude réalisé par les neurones de l'aire LIP correspondrait à l'étape de codage sensible à la numérosité (ou étape d'accumulation) et serait transformé en une représentation cardinale de la numérosité totale (ou étape de codage sélectif de la numérosité) par les neurones de la zone VIP (Roitman et al. 2007)[3]. Par ailleurs, la comparaison des latences de réponse des neurones sélectifs à la numérosité dans les régions préfrontales et pariétales indique une différenciation plus précoce des numérosités dans le profil d'activité des neurones du SIP comparativement à celui des neurones du cortex préfrontal dorsolatéral. Ces résultats suggèrent l'implication d'un réseau fronto-pariétal dans le traitement de la numérosité au sein duquel l'information numérique serait initialement extraite dans le cortex pariétal et serait transmise dans un second temps aux régions frontales pour les traitements ultérieurs.

Parallèlement, plusieurs études se sont intéressées à l'estimation de durée chez le singe, mettant en évidence la présence de neurones sensibles à cette dimension dans le cortex pariétal (Janssen & Shadlen, 2005; Leon & Shadlen, 2003), le cortex préfrontal (Genovesio, Tsujimoto &

[3] Le substrat cérébral sous-tendant ces deux étapes successives vient très récemment d'être mis en évidence chez l'être humain (Santens, Roggeman, Fias & Verguts, 2010): l'étape intermédiaire de codage sensible à la numérosité convertissant les données visuelles en un code sélectif aurait lieu au niveau de la partie postérieure du cortex pariétal supérieur alors que l'étape de codage sélectif proprement dite prendrait place au sein de la partie antérieure du SIP.

Wise, 2006; Oshio, Chiba & Inase, 2006; 2008; Sakurai, Takahashi & Inoue, 2004) et le striatum (Chiba, Oshio & Inase, 2008). Selon la région cérébrale dont ces neurones sont issus et le type de tâche au cours de laquelle ils sont enregistrés, la manière dont l'information temporelle est représentée au niveau neuronal varie. Dans le cortex pariétal postérieur (LIP) ainsi que dans le striatum, les neurones sensibles à la durée semblent coder l'information temporelle de manière quantitative et approximative, alors que les neurones du cortex préfrontal dorsolatéral représentent cette information de manière binaire ou catégorielle (Figure 1.3B).

Enfin, de façon générale, des donnés cytoarchitectoniques, de connectivité et physiologiques explorant le traitement spatial chez le singe ont permis de mettre en évidence une ségrégation fonctionnelle du sillon intrapariétal en plusieurs sous-régions, suivant un axe postéro-antérieur, et codant l'espace en fonction du niveau de référence impliqué allant de l'œil (LIP) à la main (AIP), en passant par la tête (VIP) (voir Hubbard, Piazza, Pinel & Dehaene, 2005 pour une revue; voir encadré 3 pour une illustration précise de ces trois sous-régions). De façon plus ciblée par rapport à notre thématique, deux études ont investigué la modulation de l'activité cellulaire lors des processus de comparaison de longueurs de lignes (Tudusciuc & Nieder, 2007; 2009). Des neurones répondant sélectivement à la dimension de longueur ont été enregistrés au niveau du cortex préfrontal et du cortex pariétal, plus précisément dans la profondeur du SIP (Figure 1.3C). Le profil d'activité de

Encadré 2. Origines du système de magnitude généralisée?

L'investigation de ces différents jugements de magnitude tant chez les enfants que chez les animaux pose la question du format d'origine de ces traitements cognitifs.

Selon Walsh (2003), les représentations numériques feraient initialement partie d'un système de magnitude non-symbolique indifférencié. Tout au long du développement, les interactions avec le monde extérieur vont conduire à l'affinement et la différentiation progressive de la représentation de numérosité. Cette hypothèse est basée sur l'idée que les multiples fonctions du cortex pariétal seraient de façon innée reliées à travers le concept de codage des informations de magnitude nécessaires à la réalisation des actions.

Alternativement, d'autres auteurs soutiennent l'idée que des représentations spécifiques et spécialisées se développeraient prioritairement dans le cerveau humain, les mécanismes partagés de traitement de la magnitude n'émergeant que plus tardivement, en tant que solution économique vu le haut degré de similarité existant entre les différentes représentations de magnitude (Cohen Kadosh et al., 2008).

ces neurones montrait une baisse d'activité progressive pour les longueurs s'éloignant de la longueur préférentielle (comme illustrée par les deux graphiques de la figure 1.3C). Il est important de noter que ces études se sont également intéressées, au sein du même protocole, à l'estimation de numérosité dans le but d'analyser le codage neuronal commun du traitement de ces quantités continues (i.e., la longueur) et discrètes (i.e., la numérosité). Les résultats découlant de cette comparaison directe seront développés ultérieurement dans ce manuscrit (voir point 3.2).

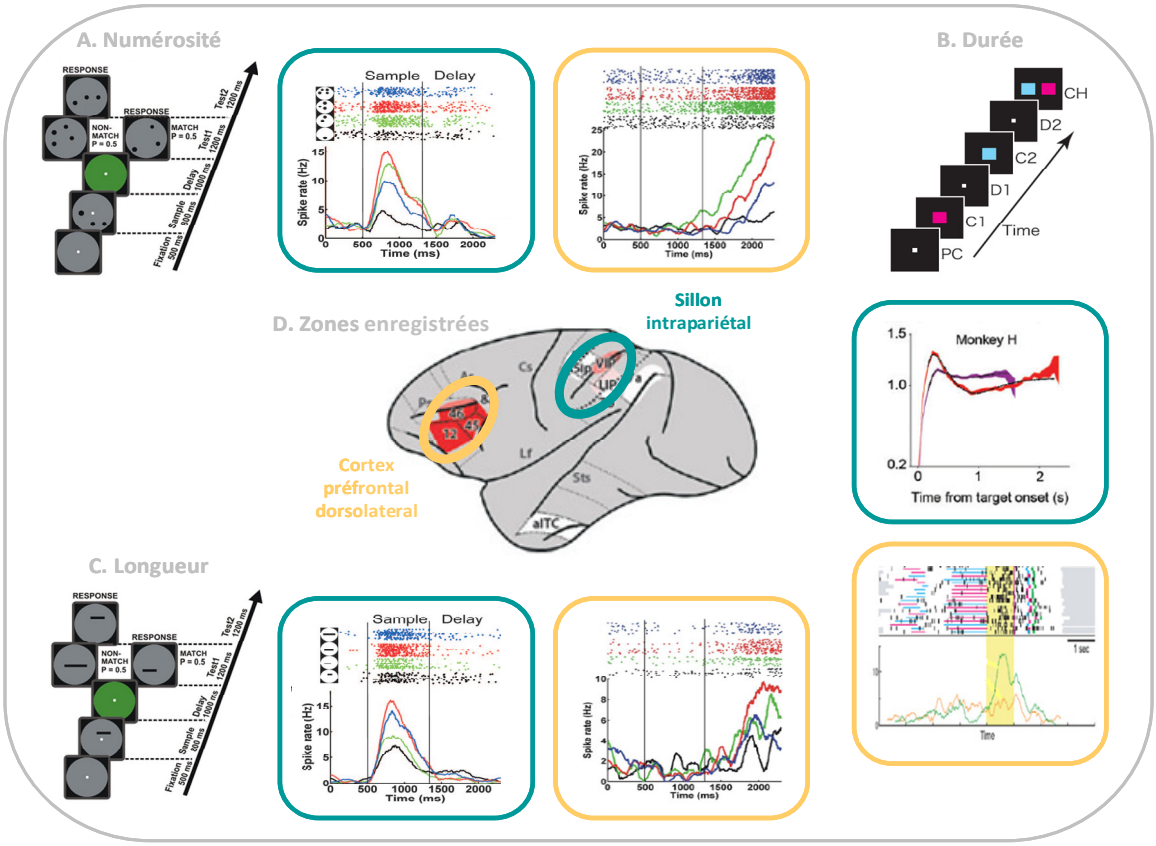

Figure 1.3: Etudes d'enregistrement neuronal investiguant les processus d'estimation de magnitude chez le singe. **A.** Exemple de protocole expérimental utilisé pour une tâche d'appariement de numérosité (Nieder et al., 2002). L'animal doit détecter si le second stimulus contient le même nombre de points que le premier *(*match) ou un nombre de points différents (non-match). Profils d'activité d'un neurone du SIP (encadré vert; d'après Nieder & Miller, 2004) et d'un neurone du cortex préfrontal (encadré orange; d'après Nieder et al., 2002) sélectif pour la numérosité 3 et 2 respectivement. Les graphiques représentent la fréquence de décharge du neurone en fonction de la numérosité présentée. Le taux de décharge est maximal pour la numérosité préférentielle et diminue parallèlement avec l'augmentation de la distance numérique par rapport à la numérosité cible. **B.** Exemple de protocole expérimental utilisé pour une tâche de discrimination de durée. Le singe doit décider lequel des deux stimuli est resté affiché le plus longtemps. Profils d'activité d'un neurone du SIP (encadré vert; d'après Janssen & Shadlen, 2005) et d'un neurone du cortex préfrontal (encadré orange; d'après Oshio et al., 2006) sélectif pour la durée. Les graphiques représentent la

fréquence de décharge du neurone en fonction de la durée présentée. Au sein du SIP, alors que le taux de décharge est maximal pour une durée préférentielle (courbe rouge), la présence d'une décharge, bien que moindre, est observée aussi pour des durées avoisinantes (courbe mauve). Par contre, dans le cortex préfrontal, les neurones déchargent de façon binaire, ne répondant ainsi qu'à une durée déterminée (courbe verte). **C.** Exemple de protocole expérimental utilisé pour une tâche d'appariement de longueurs (Tudusciuc & Nieder, 2007; 2009). La procédure est similaire à celle décrite pour la tâche de numérosité ci-dessus, à l'exception que les stimuli sont des rectangles de longueurs variables. Profils d'activité d'un neurone du SIP (encadré vert; d'après Tudusciuc & Nieder, 2007) et d'un neurone du cortex préfrontal (encadré orange; d'après Tudusciuc & Nieder, 2009) sélectif pour la longueur 3. Les graphiques représentent la fréquence de décharge du neurone en fonction de la longueur présentée. **D.** Sites d'enregistrement cellulaire (SIP et cortex préfrontal dorsolatéral) (adapté de Nieder & Dehaene, 2009). Le taux de décharge est maximal pour la longueur préférentielle et diminue au fur et à mesure que la longueur présentée diffère de la longueur préférentielle.

En résumé, quelle que soit la dimension spécifique à traiter (numérosité, durée ou encore longueur), les résultats semblent converger vers l'implication systématique de deux régions corticales lors du traitement de la magnitude chez le singe, à savoir le cortex pariétal (et plus particulièrement le SIP) et le cortex préfrontal dorsolatéral. Toutefois, ces données sont issues d'études différentes, utilisant des paradigmes expérimentaux spécifiques et enregistrant l'activité neuronale de singes différents, nécessitant dès lors d'être prudent dans la formulation de liens entre ces traitements. Des paradigmes couplant l'exploration de ces diverses dimensions apparaissent nécessaires pour proposer l'existence de liens directs. Quelques tentatives ont déjà été entreprises; elles seront décrites par la suite (voir point 3.2).

Par ailleurs, il est important de souligner que, même si cette technique d'enregistrement cellulaire appliquée chez le singe a permis de récolter des informations intéressantes quant à la localisation cérébrale du traitement de différentes magnitudes, elle comporte d'importantes limitations quant à la compréhension des fonctions cérébrales chez l'humain. D'une part, une limite possible des études neurophysiologiques, ainsi que de la plupart des études réalisées avec des animaux, réside dans le fait que ces singes sont soumis à des périodes d'entrainement massives avant la phase d'expérimentation proprement dite, pouvant entrainer des changements au niveau du tissu neuronal pendant cette période (e.g., Pascual-Leone, Amedi, Fregni & Merabet, 2005; Poldrack, 2000). D'autre part, même si des propositions d'homologies entre certaines zones

du cerveau du singe et de l'homme existent (voir encadré 3), la comparaison anatomique de ces cerveaux révèle non seulement des différences au niveau des aires corticales complexes mais également au niveau des aires sensorielles précoces (Sereno, 1998; Tootell et al., 1997). Dès lors, afin de comprendre exactement la manière dont sont représentées les magnitudes au niveau cérébral chez l'être humain, le recours aux données issues des études neuropsychologiques ou utilisant les techniques de neuroimagerie chez l'homme, comme la résonance magnétique fonctionnelle ou la stimulation magnétique transcranienne, apparait indispensable. Les paragraphes qui vont suivre s'attèleront à la description de ces études ayant investigué de façon spécifique le substrat cérébral sous-tendant une des trois dimensions nous intéressant directement, à savoir la numérosité, la durée ou la longueur.

2.3 Données neuroanatomiques chez l'être humain

2.3.1 Etudes neuropsychologiques

Si le rôle du cortex pariétal dans les traitements numériques symboliques a été démontré par de nombreuses études neuropsychologiques auprès de patients cérébrolésés (e.g., Dehaene & Cohen, 1997; Henschen, 1919; Takayama, Sugishita, Akigushi & Kimura, 1994), celles ayant investigué plus précisément l'estimation de la numérosité sont rares. Une perturbation des capacités d'estimation de collections de points a ainsi été mise en évidence chez différents patients présentant une atteinte pariétale dans l'hémisphère droit (Warrington & James, 1967). Plus récemment, des observations allant dans le même sens ont été rapportées par l'étude d'une patiente, MC, souffrant d'une lésion focale dans le cortex pariétal gauche, entre le gyrus supramarginal et le gyrus post-central (Polk, Reed, Keenan, Hogarth & Anderson, 2001). En effet, cette patiente présentait une dissociation nette entre d'une part, des capacités sévèrement altérées dans les tâches impliquant le traitement de nombres symboliques et, d'autre part, des capacités adéquates dans les tâches sollicitant le traitement de quantité à partir de stimuli non symboliques comme la comparaison de collections de points ou l'estimation de la fréquence

d'occurrence d'un événement. Ces observations tendent à suggérer une supériorité des régions pariétales droites dans la représentation de la quantité numérique non symbolique. Par ailleurs, plusieurs études indiquent qu'une lésion pariétale gauche est souvent à l'origine de troubles numériques massifs, ayant trait tant au traitement numérique symbolique qu'au traitement numérique non symbolique (Ashkenazi, Henik, Ifergane & Shelef, 2008; Cipollotti, Butterworth & Denes, 1991; Lemer, Dehaene, Spelke & Cohen, 2003). Une perturbation des capacités d'estimation de collections de points a, par exemple, été mise en évidence chez un patient présentant une atteinte focale au niveau du SIP gauche (Lemer et al., 2003). Comme le prédit le modèle du triple code (Dehaene & Cohen, 1995), il semblerait donc que les deux hémisphères cérébraux au niveau pariétal soient impliqués dans l'estimation de numérosités non symboliques, bien qu'une atteinte unilatérale puisse altérer à elle seule ce processus de quantification. Il est important de noter que l'évaluation des capacités d'estimation numérique non symbolique en tant que telle est rare, les tâches utilisées présentant souvent des patterns de points trop peu nombreux ou présentés pendant un laps de temps suffisamment important que pour permettre d'avoir recours au dénombrement.

En ce qui concerne la perception et le traitement des durées, les recherches neuropsychologiques suggèrent tout d'abord l'implication des ganglions de la base et du cervelet, suite aux performances déficitaires observées dans des tâches d'estimation temporelle respectivement chez des patients atteints de la maladie de Parkinson (Artieda, Pastor, Lacruz & Obeso, 1992; Harrington, Haaland & Hermanowicz, 1998; Malapani et al., 1998; Malapani, Deweer & Gibbon, 2002; Merchant, Luciana, Hooper, Majestic & Tuite, 2008; Pouthas & Perbal, 2004) et chez des patients cérébelleux (Casini & Ivry, 1999; Ivry, Keele & Diener, 1988; Mangels, Ivry & Shimizu, 1998; Nichelli, Alway & Grafman, 1996; Spencer, Zelaznik, Diedrichsen & Ivry, 2003). Outre cette double implication sous-corticale, selon les résultats d'une étude lésionnelle explorant un large panel de patients présentant des lésions focales, des zones frontales et

pariétales latéralisées dans l'hémisphère droit pourraient être impliquées dans la discrimination de durées en dessous de la seconde (Harrington, Haaland & Knight, 1998). En effet, seuls les patients présentant une atteinte dans l'hémisphère droit manifestaient des performances déficitaires dans une tâche de discrimination temporelle auditive. L'analyse plus approfondie de la localisation des lésions au sein de ce sous-groupe de patients rendait compte de lésions antérieures correspondant au cortex préfrontal et de lésions postérieures correspondant au cortex pariétal inférieur, suggérant qu'un réseau cérébral fronto-pariétal droit jouerait un rôle dans l'estimation de durée. D'autres études neuropsychologiques ont confirmé par la suite l'implication de ces deux aires corticales à travers différents paradigmes (e.g., Koch, Oliveri, Carlesimo & Caltagirone, 2002; pour une revue, voir Battelli, Pascual-Leone & Cavanagh, 2007; Battelli, Walsh, Pascual-Leone & Cavanagh, 2008).

Enfin, les études explorant les performances visuo-spatiales de patients présentant des lésions pariétales droites ont rapporté non seulement la présence d'une négligence spatiale controlatérale (i.e., incapacité à détecter, à s'orienter vers, ou à répondre à des stimuli présentés dans l'hémi-espace controlésionnel; Heilman, 1979) mais aussi des performances déficitaires dans des tâches de bissection de lignes (Bisiach & Luzziatti, 1978; Harvey, Milner & Roberts, 1995; Marshall & Halligan, 1989), ainsi que lors de tâches de comparaison de longueurs de lignes (Irving-Bell, Small & Cowey, 1999; Milner & Harvey, 1995). Les patients négligents présentaient en effet un biais vers la droite lorsqu'ils devaient indiquer le milieu d'une ligne au cours de tâches de bissection reflétant la négligence du côté gauche de la ligne et présentaient systématiquement une sous-estimation de la longueur des lignes présentées dans leur hémichamp controlatéral dans les tâches de comparaison de longueur.

En résumé, tout comme les études d'enregistrement cellulaire chez le singe, les recherches neuropsychologiques semblent impliquer le cortex pariétal dans le traitement de différentes magnitudes. Du point de vue de la théorie de la magnitude généralisée (Walsh, 2003),

l'ensemble de ces travaux neuropsychologiques explorant les troubles d'estimation chez des patients semble donc converger vers l'existence d'un substrat neuroanatomique commun à toutes les magnitudes traitées. Toutefois, il est important de noter que les patients étudiés présentent souvent de larges lésions, non strictement limitées au cortex pariétal, rendant dès lors la formulation de conclusions fermes et définitives difficiles (Bueti & Walsh, 2009). Bien que peu nombreuses, quelques études ont investigué l'estimation de plusieurs dimensions chez une même population de patients, démontrant ainsi soit la présence de dissociations ou d'associations de déficits. Ces recherches seront développées dans la partie consacrée aux liens entre les dimensions (voir point 3.1).

2.3.2 Etudes en neuroimagerie fonctionnelle

Parallèlement à l'évolution des technologies d'imagerie cérébrale et au développement des paradigmes expérimentaux, ces vingt dernières années ont vu se multiplier de façon considérable le nombre d'études investiguant le substrat cérébral des activités numériques, temporelles et spatiales au sens large. Dans les paragraphes qui vont suivre, seules les recherches explorant de façon spécifique les processus d'estimation des dimensions de numérosité, de durée et de longueur, telles que définies préalablement (voir encadré 1), seront abordées (Tableau 1.2).

Alors que l'implication des régions pariétales dans le traitement numérique est bien établie (pour une revue, voir Dehaene, Piazza, Pinel & Cohen, 2003), plus récemment, quelques études en imagerie cérébrale fonctionnelle se sont intéressées à l'estimation de la numérosité à partir de matériel non symbolique (e.g., des collections visuelles de points). Les résultats de ces quelques études démontrent le rôle prépondérant des régions pariétales et plus spécifiquement celles entourant les SIP dans ce processus de quantification (Figure 1.4). L'activation des SIP gauche et droit est en effet rapportée en réponse à une numérosité déviante lorsque les participants sont passivement exposés à des collections de points dans un paradigme d'habituation (Cantlon, Brannon, Carter & Pelphrey, 2006; Piazza, Izard, Pinel, Le Bihan &

Dehaene, 2004; Piazza, Pinel, Le Bihan & Dehaene, 2007). L'implication bilatérale des SIP est également démontrée lors de tâches de comparaisons de collections visuelles et/ou auditives d'éléments présentés de façon séquentielle ou simultanée (Ansari & Dhital, 2006; Castelli, Glaser & Butterworth, 2006; Piazza, Mechelli, Price & Butterworth, 2006), durant l'énumération de points (Fink et al., 2001; Piazza, Mechelli, Butterworth & Price, 2002; Piazza, Giacomini, Le Bihan & Dehaene, 2003; Sathian et al., 1999) ainsi qu'au cours d'une tâche d'addition simple sur du matériel non symbolique (Venkatraman, Ansari & Chee, 2005). Parmi ces études, certaines mettent en évidence des activations additionnelles au niveau du cortex frontal, suggérant l'intervention d'un réseau fronto-pariétal dans le traitement de la numérosité (Ansari & Dhital, 2006; Piazza et al., 2006). De plus, l'activité de ces régions cérébrales est modulée par l'effet de distance (Ansari & Dhital, 2006; Piazza et al., 2004), cette modulation ressemblant fortement à l'effet de distance observé à un niveau neuronal lors des études décrites chez le singe (Nieder & Miller, 2004).

L'ensemble des études ayant investigué les processus d'estimation temporelle au cours de tâches portant sur des durées de quelques centaines de millisecondes révèle un large réseau de régions cérébrales activées comprenant les ganglions de la base, les régions prémotrices, l'aire motrice supplémentaire et le cervelet, ainsi qu'un réseau fronto-pariétal avec une prédominance hémisphérique droite (Belin et al., 2002; Coull, Vidal, Nazarian & Macar, 2004; Ferrandez et al., 2003; Pouthas et al., 2005; Rao, Mayer & Harrington, 2001; pour une revue voir Lewis & Miall, 2003a; Macar et al. 2002; Figure 1.4). Toutefois, le rôle exact et la spécificité de ces régions par rapport aux différentes étapes de traitement de l'information temporelle fait l'objet encore à l'heure actuelle de nombreux débats. Une étude examinant plus précisément le décours temporel des activations au cours d'une tâche d'estimation de durée attribue un rôle d'horloge interne aux ganglions de la base activés précocement, qui seraient associés à un système d'allocation des ressources attentionnelles sous-tendu par le cortex pariétal inferieur droit. Les régions

prémotrices seraient quant à elles impliquées dans le maintien temporaire de l'information temporelle en mémoire de travail, alors que le cortex préfrontal dorsolatéral droit interviendrait dans des étapes plus tardives liées à la manipulation de l'information de durée nécessaire à la comparaison des intervalles et à la prise de décision (Rao et al., 2001).

Tableau 1.2: Récapitulatif des aires frontales et pariétales activées dans les études en IRMf investiguant respectivement les processus d'estimation de numérosités, de durées et de longueurs. DLPFC = Cortex dorsolatéral préfrontal; SIP = Sillon Intrapariétal; G = Hémisphère Gauche; D = Hémisphère Droit.

Dimensions	Etudes	Zones frontales	Coordonnées		Zones pariétales	Coordonnées	
			Gauche	Droite		Gauche	Droite
Numérosité	**1.** Ansari & Dhital (2006)	Lobe frontal G	-34 17 19		SIP G & D	-32 -50 44	32 -49 46
	2. Castelli et al. (2006)				SIP G & D	-24 -48 48	33 - 57 51
	3. Piazza et al. (2006)	Lobe frontal D		48 42 14	SIP D		52 -48 50
Durée	**1.** Belin et al. (2002)	Lobe frontal D		40 30 24	Lobe Pariétal Inf D		54 -50 50
	2. Coull et al. (2004)	DLPFC D		21 36 33	Lobe Parietal Inf G & D	-51 -48 33	48 -45 33
	3. Ferrandez et al. (2003)	Lobe frontal G & D	-39 9 30	45 9 36	Lobe Parietal Inf G & D	-42 -36 42	39 -45 42
	4. Pouthas et al. (2005)	DLPFC D		39 33 15	SIP D		39 -42 39
	5. Rao et al. (2001)	DLPFC D		34 23 25	SIP D		38 -40 41
Longueur	**1.** Fias et al. (2003)				SIP G	-36 -68 58	
	2. Fink et al. (2000)				Lobe Parietal Inf D		44 -32 52
	3. Fink et al. (2001)	DLPFC D		50 20 20	Lobe Parietal Inf G & D	-38 -42 40	40 -40 42
	4. Pinel et al. (2004)				SIP G & D	-36 -52 52	40 -40 44
	Coordonnées Moyennes		-37 13 25	40 28 24		-37 -49 45	42 -44 45
	Ecarts-Type		3,5 5,7 7,8	9,9 11,1 8,4		8,3 9,9 8,2	7,1 6,7 5,9

Le cortex pariétal, principalement situé dans l'hémisphère droit, ainsi que le cervelet et le cortex préfrontal constituent le substrat cérébral sous-tendant les processus d'estimation de longueur. Celui-ci a été mis en évidence au cours de tâche de bissection de lignes (Fink et al., 2000; Fink, Marshall, Weiss & Zilles, 2001), durant des tâches de jugement de taille (Pinel et al., 2004) ou lors de la comparaison de longueur de lignes (Fias et al., 2003; Figure 1.4). On notera toutefois qu'aucune de ces deux dernières études n'avaient pour objectif direct d'investiguer l'estimation de longueur ou de taille en tant que telle, cette tâche constituant une condition parmi d'autres afin de mettre en évidence les activations communes à plusieurs jugements de magnitudes. Les résultats présentés dans ces articles se focalisaient donc sur les activations communes et peu d'informations étaient disponibles sur les contrastes directs.

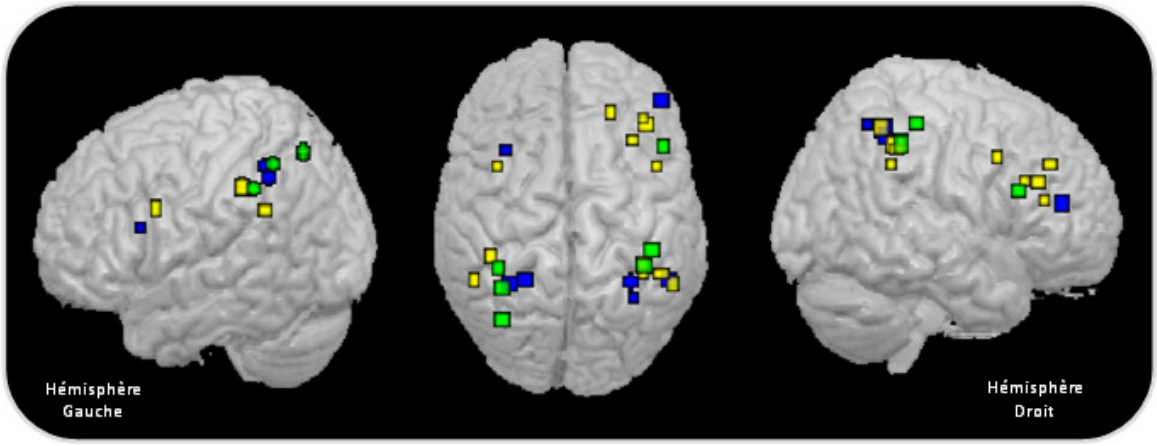

Figure 1.4: Synthèse des pics d'activation observés dans le cortex frontal et pariétal au cours de tâche d'estimation de numérosité (en bleu; Ansari & Dhital, 2006; Castelli et al., 2006; Piazza et al., 2006), de durée (en jaune; Belin et al., 2002; Coull et al., 2004; Ferrandez et al., 2003; Pouthas et al., 2005; Rao et al., 2001) et de longueur (en vert; Fias et al., 2003; Fink et al., 2000, 2001; Pinel et al., 2004). Les foyers d'activation repris dans le tableau 1.2 sont représentés sur une reconstruction en 3D d'un cerveau standard.

Comme l'illustre la figure 1.4, l'implication bilatérale des régions pariétales postérieures rapportées systématiquement lors de l'estimation de numérosité semble également être observée lors de l'estimation d'intervalles de temps et lors de jugement de longueurs. Toutefois, des données enregistrées chez un même participant (i.e., intra-sujet) sont nécessaires pour déterminer de façon exacte les foyers d'activation cérébraux identiques au sein de plusieurs tâches. L'exploration au sein d'un même paradigme de plusieurs processus d'estimation apparait donc comme indispensable afin de définir précisément le recouvrement possible entre ces zones d'activation.

2.3.3 Etudes en stimulation magnétique transcranienne (SMT)

Si ces études en imagerie fonctionnelle démontrent la présence d'un changement transitoire local de l'activité pariétale durant l'exécution de divers jugements de magnitudes, cette technique ne permet pas de révéler l'existence d'une relation causale directe entre ces changements d'activité cérébrale et leurs conséquences comportementales respectives (Sack,

2010). La stimulation magnétique transcranienne (SMT)[4] constitue une technique non invasive permettant d'investiguer ce type de relations causales (Hallett, 2000; Walsh & Cowey, 2000). Au cours de ces dernières années, cette opportunité d'interférer activement avec le traitement cérébral pendant la performance comportementale a été utilisée de façon exponentielle afin d'investiguer les fonctions cognitives supérieures, y compris les processus d'estimation de magnitude.

Si plusieurs études en SMT ont investigué le rôle des régions pariétales au cours de différentes tâches numériques portant sur du matériel symbolique (i.e., chiffres arabes; pour une revue, voir Sandrini & Rusconi, 2009), une seule étude, à notre connaissance, apporte une nouvelle preuve de la contribution du SIP à la représentation des numérosités (Cappelletti, Barth, Fregni, Spelke & Pascual-Leone, 2007). Dans cette étude, un train de stimulation à basse fréquence (15 min, 1 Hz) était appliqué sur quatre sites distincts (SIP gauche et droit, gyrus angulaire gauche et droit). Après chaque période de stimulation, les participants devaient réaliser deux tâches de comparaison (standard = 65) soit sur du matériel arabe (i.e., nombres compris entre 31 et 99) soit sur du matériel non symbolique (i.e., collections de points comprenant entre 31 et 99 points). Comparativement à la condition de contrôle (i.e., stimulation *sham*[5]), les performances des participants tant dans les tâches de comparaison numérique de nombres arabes que de collections de points étaient affectées uniquement après la stimulation du SIP gauche, suggérant le rôle prépondérant de cette zone cérébrale dans le traitement numérique et ce, indépendamment de la notation symbolique ou non symbolique des numérosités.

Plusieurs études utilisant la SMT et portant sur des tâches de discrimination temporelle de durées de quelques centaines de millisecondes ont démontré l'implication du cervelet (Koch, Oliveri, Salerno, Lo Gerfo & Caltagirone, 2007; Lee et al., 2007), du cortex préfrontal dorsolatéral

[4] Cette technique repose sur l'induction d'un champ électromagnétique en un point précis à la surface du scalp. En traversant le scalp et le crâne, ce champ permet de stimuler le tissu neuronal sous-jacent et de provoquer provisoirement une altération fonctionnelle du tissu neuronal stimulé.

[5] Il s'agit d'une stimulation reproduisant les sensations auditives d'une SMT réelle sans qu'il y ait un champ magnétique qui traverse le scalp.

droit (Jones, Rosenkranz, Rothwell & Jahanshahi, 2004; Koch, Oliveri, Torriero & Caltagirone, 2003), et du cortex temporal droit (Bueti, van Dongen & Walsh, 2008; pour une revue, voir Koch, Oliveri & Caltagirone, 2009). En outre, le rôle du cortex pariétal inférieur droit a également été observé lorsque les participants devaient réaliser une tâche de généralisation temporelle portant sur des sons de durée variable (i.e., 1200 ms ± 60, 120, 180 ou 240 ms) avant et après l'application d'un train de stimulation à basse fréquence (10 min, 1 Hz) sur le cortex pariétal inférieur gauche, droit ou le vertex (Alexander, Cowey & Walsh, 2005). Comparativement à la stimulation du vertex, seule la stimulation du cortex pariétal inférieur droit affecte les performances des participants (i.e., ralentissement des latences de réponse). De façon similaire, la stimulation de cette même région génère une augmentation de la variabilité des performances des participants au cours de tâches de généralisation temporelle portant sur des stimuli sonores légèrement plus brefs (i.e., sons entre 435 et 765 ms; Bueti, Barhami & Walsh, 2008). Comme suggéré par les études en imagerie fonctionnelle, un large réseau cortical avec une prédominance hémisphérique droite semble impliqué spécifiquement dans l'estimation de durées, aucune altération n'étant observée dans des tâches contrôles de discrimination de tonalités par exemple (Alexander et al., 2005). De plus, on notera que la stimulation du cervelet interfère davantage dans l'estimation de durée inférieures à la seconde (i.e., ± 500 ms) alors que la stimulation du cortex préfrontal dorsolatéral altère les performances lors du traitement d'intervalles légèrement plus longs (i.e., ± 2 sec; Koch et al., 2007), données confirmées très récemment par une méta-analyse d'études en IRMf (Wiener, Turkeltaub & Coslett, 2010).

L'exploration des processus de jugement de longueur présents dans des tâches de bissection de lignes a également été réalisée au moyen de la SMT, la stimulation du cortex pariétal droit reproduisant chez des individus sains les déficits spécifiques observés chez les patients cérébrolésés présentant une héminégligence spatiale (e.g., Bjoertomt, Cowey & Walsh, 2002; Fierro et al., 2000; Fierro, Brighina, Piazza, Oliveri & Bisiach, 2001). Ce biais vers la droite est

observé lorsque la stimulation est appliquée très précocement après l'affichage du stimulus (i.e., 50 ms; Pourtois, Vandermeeren, Olivier & de Gelder, 2001) et n'apparaît que lorsque ce dernier est présenté dans l'espace proche du participant (Bjoertomt et al., 2002; Bjoertomt, Cowey & Walsh, 2009). Hormis les études utilisant un paradigme de bissection de lignes, aucune étude en SMT ne s'est, jusqu'à présent, intéressée à la comparaison explicite de longueurs.

L'utilisation de cette technique récente, permettant d'investiguer la mesure dans laquelle une région cérébrale contribue de façon nécessaire à un processus cognitif particulier en provoquant des modifications provisoires et réversibles de ces fonctions cognitives, a démontré le rôle prépondérant et décisif du cortex pariétal dans les différents jugements de magnitude. Toutefois, toutes ces études ne présentent pas le même degré de précision quant au mode de définition des sites de stimulation, les méthodes utilisées allant des repères classiques du système international de localisation 10-20 EEG au système de neuronavigation guidée par les images anatomiques voire fonctionnelles. Le système 10-20 EEG localisant des électrodes sur le scalp en utilisant des repères standards du crâne (Jaspers, 1958), les difformités et asymétries du crâne et du cerveau sont à l'origine d'imprécisions importantes lors de la détermination des sites de stimulation. Les techniques plus récentes de coregistration neuronaviguées utilisent quant à elles des données structurelles ou fonctionnelles issues de l'imagerie par résonance magnétique afin de localiser les aires cérébrales sur le crâne des participants. Cette méthodologie permet d'atteindre une précision de localisation importante, éliminant les problèmes liés à la variabilité structurelle et/ou fonctionnelle de l'anatomie cérébrale chez l'humain. Etant donné la variabilité des méthodes de coregistration utilisées au cours des différentes études décrites ci-avant, il est dès lors difficile d'affirmer que les zones cérébrales stimulées étaient exactement identiques d'une étude à l'autre, et la formulation de conclusions concernant l'implication commune de certaines régions est dès lors impossible sur base de ces résultats. A nouveau, l'investigation de plusieurs dimensions au sein d'une même étude utilisant un système de neuronavigation

développé et fiable constituerait une des solutions envisageables afin de contourner les limites précitées.

Si l'ensemble de ces études abordant de façon séparée le traitement d'une des magnitudes semble dégager de nombreuses similitudes et impliquer de façon récurrente le cortex pariétal comme substrat cérébral commun sous-tendant les processus d'estimation, des études investiguant les relations fonctionnelles et anatomiques directes pouvant exister entre ces différentes dimensions sont nécessaires. Celles-ci feront l'objet du point suivant.

3. Liens entre les processus d'estimation de magnitude

3.1 Données comportementales

Suite notamment à la proposition ATOM (Walsh, 2003), diverses études se sont intéressées aux interactions comportementales pouvant exister entre plusieurs dimensions de magnitude et ce, principalement au moyen de paradigmes d'interférence explorant l'influence d'une dimension non-pertinente sur le jugement d'une autre dimension.

Tout d'abord, un effet d'interférence robuste des dimensions numériques tant sous forme symbolique que non symbolique, a été observé au cours de tâches de comparaison de durées (Brown, 1997; Oliveri et al., 2008; Roitman, Brannon, Andrews & Platt, 2007; Vicario et al., 2008; Xuan, Zhang, He & Chen, 2007; voir la figure 1.5 pour un exemple de paradigme). Par exemple, bien que non pertinente pour la tâche, la magnitude de chiffres arabes interfère avec le jugement de durée: lorsque les participants doivent estimer la durée de présentation d'un chiffre arabe, ils sous-estiment la durée des petits chiffres et inversement, ils surestiment la durée des grands chiffres (Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007). De plus, la numérosité de collections de points présentées visuellement interagit avec la comparaison de durée: les indices numériques facilitent le jugement de durée lorsqu'ils sont congruents et interfèrent avec celui-ci lorsqu'ils sont incongruents (Xuan et al., 2007). Par contre, l'influence inverse des dimensions temporelles sur le jugement de numérosités, bien que nettement moins explorée, semble moins

prédominante (uniquement rapportée chez Brown, 1997). Des résultats similaires ont également été observés chez des enfants de 5 et 8 ans dans des tâches de bissection numérique et temporelle de séquences de points, un effet d'interférence unilatérale des indices numériques sur les performances temporelles étant rapporté (Droit-Volet, Clément & Fayol, 2003).

Ensuite, naturellement reliées à travers le concept de vitesse, les dimensions de durée et d'espace ont fait l'objet de plusieurs études investiguant l'effet des indices spatiaux sur la discrimination de durées (voir la figure 1.5 pour un exemple de paradigme). Les résultats de ces études démontrent une forte influence de la dimension spatiale sur le traitement de la durée, les indices congruents ou incongruents entrainant respectivement des effets de facilitation (i.e., une diminution des latences de réponses et/ou des pourcentages d'erreurs) et d'interférence (i.e., une augmentation des latences de réponse et/ou des pourcentages d'erreurs). Ainsi, la taille de formes géométriques (Xuan et al., 2007), la longueur de séquences de points (Casasanto & Boroditsky, 2008) ou encore le côté de l'espace dans lequel les stimuli sont présentés (Vicario et al., 2008) peuvent affecter le jugement de durée: la durée de présentation de petites formes, de séquence courtes ou d'un point présenté dans l'hémichamp gauche sera sous-estimée, alors qu'inversement une surestimation sera observée lors de l'estimation de la durée de présentation de grandes formes, de séquences longues ou d'un point présenté dans l'hémichamp droit. Cette interaction spatiale sur le jugement de durée est présente également chez les enfants. Ainsi, le jugement de la vitesse d'un train est influencé par la taille de celui-ci (Stavy & Tirosh, 2000): à vitesse constante, un grand train apparaitra comme roulant plus vite qu'un train de plus petite taille. L'estimation de la durée de présentation d'un signal lumineux dépend également de sa taille ou de sa luminosité (Levin, 1977; 1979; 1982).

Enfin, l'existence d'une association entre la numérosité et l'espace est communément et largement acceptée, celle-ci ayant été démontrée à travers divers paradigmes. Il est toutefois important de noter que la notion d'espace peut comprendre une large variété de processus

moteurs et cognitifs. Ici, seules les expériences abordant la dimension spatiale sous la forme stricte de discrimination d'une longueur déterminée par deux bornes seront abordées. Des effets d'interférence réciproque et mutuelle ont été rapportés, notamment dans des tâches de bissection de lignes (de Hevia & Spelke, 2009; Fischer, 2001; voir la figure 1.5 pour un exemple de paradigme), de reproduction de longueurs (de Hevia, Girelli, Bricolo & Vallar, 2008) ou encore lors d'une tâche de comparaison de taille physique ou numérique de chiffres arabes (e.g., Henik & Tzelgov, 1982). Ainsi, par exemple, un biais systématique envers la magnitude la plus élevée est observé lors de la bissection de lignes horizontales flanquées de deux chiffres arabes (Fischer, 2001) ou de deux collections de points (de Hevia & Spelke, 2009). De plus, dans des tâches de comparaison de la taille numérique ou physique de chiffres arabes, lorsque ces deux dimensions sont manipulées indépendamment, les résultats montrent une interférence des indices spatiaux sur la comparaison numérique et inversement (Henik & Tzelgov, 1982). Chez les enfants, l'interférence spatiale sur les jugements de numérosités est fréquemment observée. Lorsque deux rangées comprenant le même nombre d'éléments sont de longueurs différentes, ils décident de façon erronée que la plus longue rangée contient le plus grand nombre d'objets (Gelman, 1972; Piaget & Szeminska, 1941; Pufall & Shaw, 1972), suggérant l'utilisation d'une stratégie visuo-spatiale, pertinente dans la majorité des cas, associant automatiquement longueur et nombre comme covariées (Houdé, 1997). Chez l'adulte, la comparaison correcte sur ce type de matériel conflictuel nécessite l'inhibition de cette stratégie, ce qui se traduit par un allongement des temps de réaction (Dempster, 1995; Dixon, 1978; Houdé & Guichart, 2001; Pascual-Leone, 1988). En outre, une interférence réciproque entre les informations numériques et perceptives a été observée chez des enfants dès l'âge de 3 ans (Rousselle & Noel, 2008). La comparaison numérique de collections de points ou de barres verticales était influencée par la surface occupée par ces éléments et vice versa, démontrant le traitement automatique précoce des dimensions spatiales et numériques respectivement.

Actuellement, une seule étude a rassemblé au sein d'une même expérience ces trois dimensions quantifiables afin d'explorer l'influence des indices numériques et spatiaux sur la perception de la durée d'intervalles (Vicario et al., 2008). Les participants devaient juger la durée de présentation d'un chiffre arabe présenté dans la partie gauche ou droite de l'écran. Outre la présence d'un effet d'interférence respectif des indices spatiaux et numériques sur les performances d'estimation temporelle des participants (voir ci-avant), un effet conjoint a pu être mis en évidence lorsque ces deux dimensions étaient manipulées de façon simultanée. La durée de présentation des petits chiffres (i.e., 1) était d'autant plus sous-estimée lorsqu'ils étaient présentés dans l'hémi-espace gauche, et inversement, la durée de présentation des grands chiffres (i.e., 9) était davantage surestimée lorsqu'ils étaient présentés dans l'hémi-espace droit.

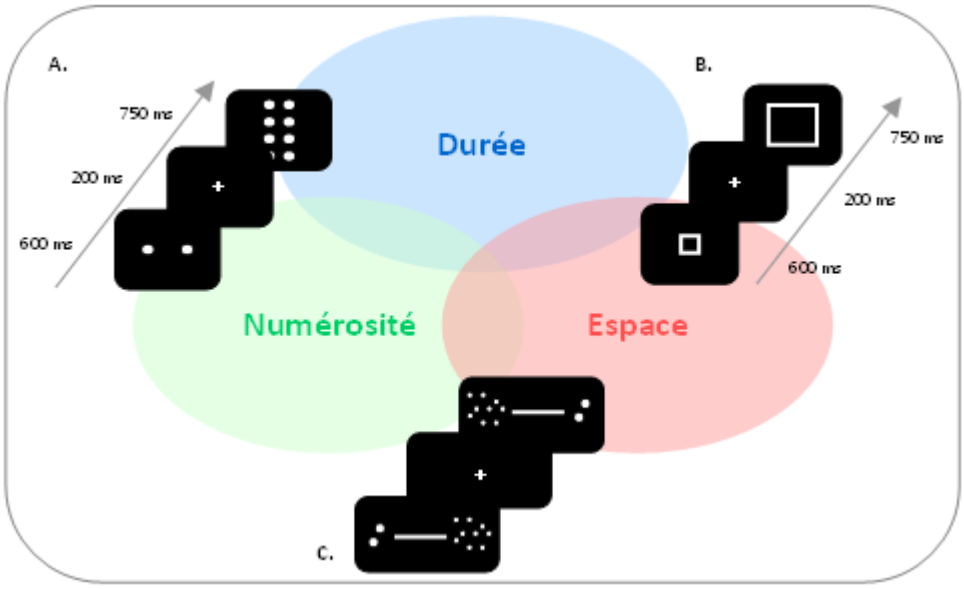

Figure 1.5: Exemples de paradigmes expérimentaux investiguant les effets d'interférence entre plusieurs magnitudes. (A) Tâche de comparaison de durées: la numérosité représentée par les collections de points interfèrent avec le jugement de durée de présentation de ces collections (d'après Xuan et al., 2007), (B) Tâche de comparaison de durées: la taille des formes géométriques interfère avec le jugement de durée de présentation de ces formes (d'après Xuan et al., 2007) et (C) Tâche de bissection de lignes: la numérosité des collections de points situées aux extrémités des lignes interfère avec la bissection de ces lignes horizontales (d'après de Hevia et al., 2009).

Si toutes ces études ont tenté de refléter comment ces dimensions interagissent entre elles, on soulignera que la plupart n'ont exploré les interactions que de façon unilatérale et en

utilisant généralement du matériel biaisé (e.g., des stimuli dont la taille des éléments et leur espacement étaient constants, ou des séquences sonores où la durée covariait explicitement avec le nombre d'éléments). Jusqu'à présent, les interactions mutuelles et bidirectionnelles de la durée, de la numérosité et de la longueur au sein d'un seul et même paradigme expérimental n'ont donc pas été examinées.

3.2 Données neurophysiologiques chez le singe

Récemment, deux études d'enregistrement cellulaire ont investigué le codage neuronal de plusieurs magnitudes chez les mêmes singes (Tudusciuc & Nieder, 2007; 2009), afin de tester si les neurones connus pour être sensibles à la numérosité pouvaient être sensible à d'autres variables continues, comme la longueur dans le cas présent. Les caractéristiques de réponse des neurones situés dans la partie ventrale du sillon intrapariétal (VIP) et dans le cortex préfrontal de singes rhésus ont été analysées lorsque

Encadré 3. Homologies fonctionnelles entre le cortex pariétal du singe et de l'homme

Chez le singe, comme mentionné ci-avant, le SIP est subdivisé en plusieurs sous-régions selon un axe postéro-antérieur, codant les informations de référence spatiale relative à l'œil (LIP), à la tête (VIP) ou à la main (AIP; voir Hubbard et al, 2005 pour une revue; voir Figure 1.6).

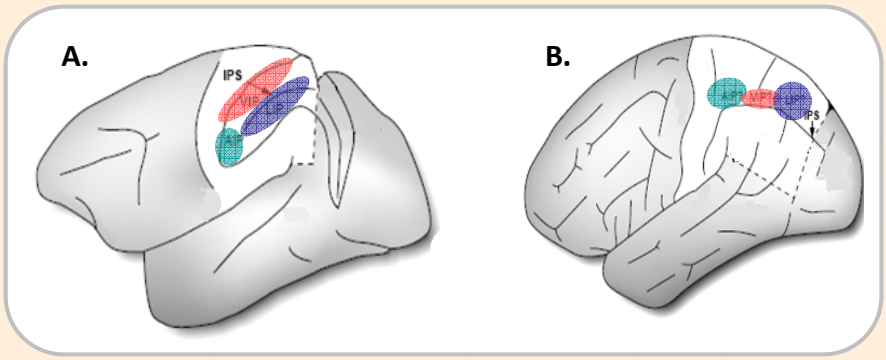

Figure 1.6 : Comparaison du SIP chez le macaque et l'humain. Vue latérale d'un cerveau (A) simien et (B) humain. Chez le singe, le SIP est composé notamment de la sous-région antérieure (AIP; en vert), ventrale (VIP; en rose) et latérale (LIP; en bleu). Dans le SIP humain, certaines zones ont été proposées comme étant les possibles sous-régions homologues correspondantes (adapté de Culham & Kanwisher, 2001).

Chez l'être humain, des études en IRMf ont utilisé des tâches inspirées de celles utilisées chez le singe afin d'identifier les zones homologues possibles des régions intrapariétales du macaque. Les résultats ont confirmé la présence d'une organisation postéro-antérieure (Bremmer et al., 2001; Orban, Van Essen & Van Duffel, 2004; Sereno & Huang, 2006). De façon intéressante, l'aire VIP constitue un homologue plausible chez le singe, du segment horizontal du SIP activé chez l'homme lors du traitement de numérosité (e.g., Piazza et al., 2006; Castelli et al., 2006). De plus, les caractéristiques de codage de réponse de cette zone cérébrale au cours d'un paradigme d'habituation sont similaires à celles observées chez le singe (Piazza et al., 2004).

ces derniers réalisaient une tâche de discrimination de numérosités et de longueurs. Les résultats ont montré qu'alors que certains neurones répondaient sélectivement à la numérosité ou à la longueur, d'autres répondaient aux deux dimensions indifféremment, suggérant l'existence de trois populations neuronales distinctes se chevauchant en partie et représentant les informations de quantité. Enfin, une dernière recherche s'est intéressée plus spécifiquement au rôle du SIP dans la perception de numérosités présentées séquentiellement d'une part, et simultanément, d'autre part, correspondant donc respectivement à une présentation inscrite dans la durée ou dans l'espace (Nieder, Diester & Tudusciuc, 2006). De nouveau, trois populations neuronales différentes sensibles à la numérosité ont été identifiées; les deux premières rassemblent des neurones dont l'activité est dépendante du mode de présentation (i.e., une population répondait spécifiquement aux numérosités séquentielles et l'autre population aux numérosité simultanées) alors que la troisième population décharge uniquement au cours de la période de délai de rétention et ce, quel que soit le mode de présentation des numérosités.

Ces résultats sont en accord avec la présence de populations de neurones impliquées dans la perception de la numérosité et d'autres dimensions, se chevauchant partiellement au sein du SIP chez l'adulte humain, comme les prochaines pages vont le démontrer. Notons qu'aucune étude d'enregistrement neuronal n'a, jusqu'à présent, investigué simultanément les processus de traitement de la durée et de la numérosité.

3.3 Données neuroanatomiques chez l'être humain

3.3.1 Etudes neuropsychologiques

Quelques rares études ont tenté de mettre en évidence la présence d'associations ou de dissociations de déficits dans l'estimation de plusieurs dimensions quantitatives, principalement chez des patients présentant des lésions au niveau du cortex pariétal. Ainsi, chez des patients héminégligents, connus pour éprouver des difficultés dans des tâches de bissection de lignes (Irving-Bell et al., 1999; Marshall & Halligan, 1989), des déficits similaires ont été observés dans

des tâches de bissection d'intervalles numériques (Cappelletti, Freeman & Cipolotti, 2007; Zorzi, Priftis & Umilta, 2002; Zorzi, Priftis, Meneghello, Marenzi & Umilta, 2006) et d'intervalles temporels (Basso, Nichelli, Frassinetti & di Pelligrino, 1996; Danckert et al., 2007). En effet, d'une part, ces études réalisées avec des patients présentant une lésion cérébrale dans l'hémisphère droit avec héminégligence gauche persistante, ont démontré que ces patients déplaçaient de façon erronée la valeur centrale d'un intervalle numérique lors de tâches de bissection (e.g., ils désignaient 5 comme le centre de l'intervalle 2-6). Ce déficit semble par ailleurs dépendant de l'orientation de la ligne mentale (Cappelletti et al., 2007), ce biais n'étant pas systématiquement présent lorsque la bissection s'opérait sur une représentation verticale. D'autre part, l'exploration de la comparaison et de la production d'intervalles temporels inférieures à la seconde chez un patient présentant une héminégligence gauche a mis en évidence une surestimation systématique de la durée de stimuli présentés dans l'hémichamp négligé (Basso et al., 1996). Par contre, lorsqu'ils doivent estimer des intervalles de plusieurs secondes, un groupe de patients héminégligents présentant des lésions hémisphériques droites sous-estiment largement les durées présentées (Danckert et al., 2007). L'ensemble de ces données suggèrent l'existence d'une association de troubles dans l'estimation de ces différentes magnitudes chez les patients héminégligents.

Inversement, une étude de cas unique avec un patient présentant une lésion temporo-pariétale dans l'hémisphère droit, la seule à ce jour explorant les trois types de jugement de magnitude (i.e., numérique, temporel et spatial) ainsi que quelques interactions entre plusieurs de ces dimensions (i.e., durée/nombre et espace/nombre), révèle plutôt la présence d'une dissociation entre ces dimensions (Cappelletti, Freeman & Cipolotti, 2009). En effet, alors que le patient est en difficulté lors des traitements temporels, ses capacités de comparaison de numérosité et de longueur sont totalement préservées. De plus, les performances du patient reproduisent l'effet d'interférence unilatéral de la durée sur le jugement numérique ainsi que les

effets réciproques entre les nombres et l'espace rapportés dans la littérature chez les participants sains. Bien qu'il semble exister un recouvrement entre les dimensions de numérosité, de durée et de longueur comme en témoignent les effets d'interférence, les auteurs postulent que ce recouvrement ne serait que partiel. Les résultats de cette étude de cas unique suggèrent donc l'existence d'un mécanisme spécifique et partiellement indépendant, dédié au traitement de la durée et déficitaire chez ce patient.

3.3.2 Etudes en neuroimagerie fonctionnelle

Quelques recherches ont investigué plus précisément les substrats neuroanatomiques communs à plusieurs magnitudes, en examinant si les régions cérébrales impliquées dans les traitements numériques étaient également activées lors du traitement d'autres dimensions continues comme la taille, la luminosité, l'amplitude ou la longueur (Cohen Kadosh et al., 2005; Fias et al., 2003; Pinel et al., 2004). Alors que certains résultats semblent démontrer la présence d'une activité convergente au sein du SIP gauche pour la comparaison de longueur de lignes, d'amplitudes angulaires ou de paires de nombres (Fias et al., 2003), des activations associées spécifiquement à la taille physique ou numérique ont été identifiées comme se distribuant le long du SIP, et se chevauchant de façon partielle uniquement (Pinel et al., 2004). Ensemble, ces résultats suggèrent que la population neuronale codant la dimension numérique est hautement distribuée au sein du SIP, entrelacée voire se chevauchant avec la représentation d'autres paramètres quantitatifs, rejoignant ainsi les observations récoltées récemment chez le singe (Tudusciuc & Nieder, 2007; 2009).

Il est toutefois important de souligner que toutes ces études ont considéré le traitement numérique à partir de matériel symbolique (i.e., nombres à 1 ou 2 chiffres arabes), connu pour activer préférentiellement l'hémisphère dominant pour le langage. A ce jour, une seule étude a tenté d'examiner de façon directe si certaines régions pariétales étaient spécifiquement sollicitées par le traitement de quantités discrètes comparativement au traitement de quantités continues,

en utilisant du matériel exclusivement non symbolique (Castelli et al., 2006). Ces quantités étaient représentées par des collections de formes géométriques vertes et bleues changeant de manière abrupte (i.e., quantités discrètes) ou progressive (i.e., quantités continues) et ce, dans le temps (i.e., présentation successive de carrés verts et bleus) ou dans l'espace (i.e., présentation simultanée de rectangles verts et bleus). Tous les stimuli étaient composés de vingt éléments (bleus et verts) au total et les participants devaient effectuer une tâche de jugement de couleur consistant à déterminer, pour chaque stimuli présenté, s'il contenait plus de bleu ou plus de vert. Une activation plus importante des SIP a été mise en évidence lors du traitement des stimuli discrets, suggérant une représentation spécifique au sein de ces régions pour les dimensions dénombrables.

4. Synthèse & questions expérimentales

4.1 Synthèse

En conclusion, les capacités de discrimination des numérosités, des durées et des longueurs sont observables tant chez l'animal que chez l'homme et elles se manifestent précocement au cours de l'ontogenèse. Ces trois processus d'estimation partagent de nombreux effets comportementaux classiques et semblent évoluer identiquement au cours du développement. Toutefois, certaines divergences existent, que ce soit au niveau de la généralisation fonctionnelle ou au niveau du développement de la précision des différents jugements. Les études neurophysiologiques récentes chez le primate, dotées d'une précision d'enregistrement de l'ordre du neurone, convergent vers l'implication d'un réseau fronto-pariétal quelle que soit la dimension de magnitude à traiter. Enfin, la revue des littératures spécifiques et distinctes sur les substrats neuroanatomiques de l'estimation de la numérosité, de la durée et de la longueur chez l'homme suggère un rôle prépondérant du cortex pariétal dans ces trois processus cognitifs. Bien que la combinaison de ces nombreuses études semble appuyer favorablement la théorie de la magnitude généralisée (Walsh, 2003), les recherches ayant

investigué de manière directe les liens fonctionnels et neuroanatomiques existant entre ces processus sont rares. En effet, relativement peu d'études ont examiné ces liens et leurs résultats aboutissent à des résultats parfois contradictoires. D'une part, les études comportementales abordant les interactions entre plusieurs magnitudes semblent indiquer l'existence d'une représentation numérique partagée avec d'autres dimensions non numériques. Néanmoins, ces résultats peuvent refléter l'implication d'un mécanisme périphérique commun (e.g., un mécanisme de comparaison) et pas nécessairement celle d'une représentation interne commune (Cohen Kadosh et al., 2008). D'autre part, certains résultats neuroanatomiques corroborent les données comportementales, démontrant l'activation conjointe du SIP au cours de jugement de diverses magnitudes. Par contre, une partie des données en neuroimagerie s'accorde avec l'existence de mécanismes distincts et d'une ségrégation nette entre les activations récoltées au niveau intrapariétal. Enfin, similairement aux données neurophysiologiques disponibles chez le singe, l'existence conjointe de mécanismes partagés et distincts, reflétée par des activations distribuées au sein du SIP et se chevauchant partiellement, a également été rapportée. La présence chez un patient présentant une lésion temporo-pariétale droite d'une atteinte spécifique du traitement de la durée, alors que les performances dans d'autres types d'estimation de magnitude comme la longueur ou la numérosité sont intactes, à laquelle s'ajoute l'observation d'effets d'interférence entre ces différentes magnitudes (Cappelletti et al., 2009), est en accord avec l'idée de l'existence de représentations spécifiques et partiellement distinctes. L'interprétation des données actuelles en IRMf en termes de populations neuronales distinctes ou de recouvrement neuronal nécessite toutefois beaucoup de prudence. Cette technique, et particulièrement l'utilisation d'un plan expérimental soustractif simple, ne permet pas d'atteindre un degré de précision suffisant pour pouvoir établir une distinction fonctionnelle entre des populations de neurones entremêlées (Piazza & Izard, 2009). L'utilisation de techniques et/ou d'analyses plus développées pourrait permettre de résoudre ces questions. De plus, la multiplication des tâches et des stimuli utilisés pourrait entrainer des activations différentes,

reliées au paradigme expérimental et non à la dimension traitée en tant que telle. Une uniformisation ainsi qu'un contrôle strict des paramètres des tâches expérimentales apparaissent donc comme nécessaires.

4.2 Questions expérimentales

Après cette revue de la littérature concernant les différents processus d'estimation de magnitude et la mise en évidence d'un certain nombre de limites, la partie suivante abordera la contribution expérimentale de ce travail, avec pour principal objectif de dégager les éventuels interactions fonctionnelles ainsi que la spécificité et/ou la communauté des substrats neuroanatomiques des mécanismes de traitement de la numérosité, de la durée et de la longueur. Cette partie sera articulée autour de trois questions principales, abordées dans huit chapitres correspondant chacun à une recherche expérimentale. Ainsi, les relations entre le traitement de la durée et de la numérosité d'une part et celles entre le traitement de la longueur et de la numérosité d'autre part seront respectivement et systématiquement abordées sous trois angles différents, correspondant à une technique expérimentale d'investigation spécifique et répondant chacun à une de nos trois questions: **(1)** Tout d'abord, quelles sont les interactions fonctionnelles entre les différents processus d'estimation de magnitude ? Dans quelle mesure, lorsqu'on est confronté à plusieurs dimensions simultanément, celles-ci vont-elle interagir ? Des études **comportementales** tenteront de déterminer l'existence d'effets d'interférence et de facilitation entre les dimensions de magnitude et d'en préciser leur nature (i.e., unilatérale ou réciproque ?). Ces effets seront explorés tout d'abord entre les dimensions de durée et de numérosité (chapitre 2), de longueur et de numérosité ensuite (chapitre 5) et enfin, entre ces trois dimensions simultanément (chapitre 8). **(2)** Quels sont les substrats anatomiques communs entre les différents processus d'estimation de magnitude ? Grâce à des études en **IRMf**, les zones cérébrales activées distinctement et communément par la comparaison de durée et de numérosité d'une part (chapitre 3), de longueur et de numérosité d'autre part (chapitre 6), et par

la numérosité présentée à travers le temps (i.e., présentation séquentielle) ou à travers l'espace (i.e., présentation simultanée; chapitre 9) seront mises en évidence. **(3)** Enfin, les zones intrapariétales connues pour être activées dans le traitement numérique symbolique jouent-elles un rôle nécessaire dans l'estimation de la numérosité ? De plus, ces aires cérébrales sont-elles également impliquées de façon critique dans l'estimation de la durée et de la longueur ? Si les études en IRMf vont mettre en évidence les zones cérébrales activées dans les différents processus d'estimation, des études utilisant la technique de **SMT** permettront quant à elles d'établir les liens causaux existant entre les activations cérébrales rapportées et le processus de traitement en tant que tel. Ces liens seront investigués respectivement au cours du traitement de numérosité et de durée (chapitre 4) et lors de la catégorisation de numérosités et de longueurs (chapitre 7).

4.3 Introduction à la première partie expérimentale

Les trois premiers chapitres aborderont donc les interactions fonctionnelles et anatomiques existant entre les dimensions de numérosité et de durée. Dans une première étude comportementale (**chapitre 2**), un paradigme de type Stroop a été utilisé afin de tester l'éventuelle présence d'effets de facilitation et/ou d'interférence entre les dimensions temporelles et numériques. Ensuite, dans le **chapitre 3**, une comparaison directe des processus d'estimation de numérosité et de durée grâce à la technique de l'IRMf a été réalisée afin de tenter de dégager les zones cérébrales sous-tendant ces deux traitements cognitifs. Enfin, afin de compléter l'investigation des liens neuroanatomiques directs pouvant exister entre l'estimation de durée et de numérosité, l'utilisation de la SMT est apparue comme une technique complémentaire idéale (**chapitre 4**).

Chapitre 2

Numerosity-duration interference: A Stroop experiment

Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal, Seron & Pesenti (2006), publié dans *Acta Psychologica*, *121*, 109-124.

1. Abstract

The existence of a possible common mechanism for duration and numerosity processing was tested with a Stroop task. Participants had to compare either the duration or the numerosity of sequences of flashing dots for which duration and numerosity were independently manipulated to create congruent, incongruent or neutral pairs. Results show that the numerical cues interfered with duration processing, whereas the temporal cues did not interfere with numerosity processing. These findings extend the idea of an automatic access to magnitude to non symbolic sequentially presented material, and reflect a probable difference in the mandatory processing of numerosity and duration.

2. Introduction

Animal data show that various species can discriminate numerosities (Breukelaar & Dalrymple-Alford, 1998; Davis & Pérusse, 1988) and duration (Roberts & Church, 1978) in experimental as well as in natural conditions (McComb, Packer & Pusey, 1994). There is also clear evidence that newborn babies and young children experience time and have a precocious temporal representation (for a review, see Pouthas & Jacquet, 1987). Moreover, they may be sensitive to the numerosity features of the stimuli with which they are confronted, this sensitivity resulting in a broad range of numerical skills (Starkey & Cooper, 1980; Xu & Spelke, 2000; but see Mix, Huttenlocher & Levine, 2002, for a discussion of the alternative view that babies and young children may rely more on physical quantity than numerosity processing). It has been proposed that a single representational mechanism, namely an accumulator, could underlie these two estimation processes (Meck & Church, 1983). Such an internal accumulator would represent the duration or the numerosity of objects or events through different operative modes, by summing the impulses produced by a generator either at a given frequency for duration processing or each time an event or an object was encountered for numerosity processing (Meck, 1997; Meck & Church, 1983; Meck, Church & Gibbon, 1985). According to some authors, the human brain possesses an innate mechanism for the apprehension of numerical quantities inherited from the animal world (Dehaene, Dehaene-Lambertz & Cohen, 1998; Gallistel & Gelman, 1992). Early numerical abilities in infants may be grounded on preverbal processes, similar to an accumulator, from which adult arithmetical abilities develop on a kind of mental number line. These elementary numerical skills shared by animals, infants and adults would rely on a cerebral network located in the inferior parietal cortex (Dehaene, 2002; Dehaene & Changeux, 1993; Dehaene & Cohen, 1997).

Anatomo-functional data partly support the idea of a common neural substrate for duration and numerosity processing mechanisms as these data show various degrees of

implication of the parietal cortex in the processing of duration and numerosity. Neuropsychological and recent brain imaging studies suggest that time perception and processing involve the frontal cortex, the cerebellum and the basal ganglia, since lesions to these structures lead to impairments of time perception (Harrington et al., 1998; Jueptner et al., 1995; Nichelli et al., 1996). Other studies reveal the involvement of the inferior parietal cortices in time-estimation and comparison tasks, mainly in the right hemisphere (Lejeune et al., 1997; Maquet et al., 1996), and a bilateral involvement of the intraparietal areas in auditory and visually presented temporal rhythmic patterns (Schubotz, Friederici & von Cramon, 2000). Finally, the temporal allocation of attention (e.g., cued allocation of attention across delays) has been found to produce a left-sided activation in the intraparietal sulcus (Coull, 2004). The role of the parietal areas in numerical processing was demonstrated by neuropsychological studies with brain-damaged patients (Dehaene & Cohen, 1997; Takayama et al., 1994) and by brain-imaging studies using numerical comparison tasks (Pesenti, Thioux, Seron & De Volder, 2000; Pinel et al., 1999) and simple arithmetic tasks (Simon, Mangin, Cohen, Le Bihan & Dehaene, 2002). Areas along the intraparietal sulcus (perhaps its horizontal segment) appear to process numerical quantities whereas a bilateral posterior superior parietal system plays a role in attention orientation on the mental number line (Dehaene et al., 2003). The activation of a network including intraparietal, dorsolateral prefrontal, premotor areas as well as the anterior cingulate cortex was observed when subjects had to estimate the numerosity of temporal series of visually and auditory presented stimuli (Piazza et al., 2002; Piazza et al., 2006). After reviewing a broad range of behavioural, physiological, developmental, lesional and neuroanatomical data on magnitude processing, Walsh (2003) recently proposed the existence of a generalised magnitude system for the processing of time, size, quantity and space, located in the parietal cortex. For example, application of transcranial magnetic stimulation (TMS) to the parietal cortex was shown to affect the judgements of time, size and number (Göbel, Walsh & Rushworth, 2001; Hodinott-Hill, Thilo, Cowey & Walsh, 2002). The selective implication of parietal neurons was also identified in single-cell registration studies

of a judgement of numerical quantity in non-human animals (Sawamura et al., 2002) and during the estimation of duration (Leon & Shadlen, 2003; Onoe et al., 2001).

While these data correspond to the idea of a generalised magnitude system, possibly located in the parietal cortices, they should nevertheless be considered with caution for several reasons. Firstly, several studies have challenged the idea of common processes for numerosity and time estimation due to dissimilarities in animal data concerning the shapes of the functions fitting training curves (e.g., linear *vs.* power functions for numerosity and time discrimination; for a review, see Hobson & Newman, 1981). Secondly, some studies have shown that when animals were able to process the duration and the numerosity of events, they answered on the basis of numerosity only when other parameters (such as duration) were not available, suggesting that numerosity and duration processing may be more dissociated than previously assumed. For example, birds would rather base their choice on the time elapsed than on the number of events occurring during an interval (Lydersen & Crossman, 1974). This tendency was also found with rats in a task using ambiguous stimuli (i.e., with a different answer - left or right lever - for the temporal and numerical dimensions): the rats answered primarily according to the temporal dimension (Breukelaar & Dalrymple-Alford, 1998). Conversely, in other studies, numerosity constituted the fundamental condition of control for discriminations based both on time and on number (Rilling, 1967). In a tapping task, where human participants had to press a button as rapidly as possible until they felt they had reached a given number of presses, and then had to reproduce a temporal interval equivalent to the time necessary to carry out the presses, performance on the numerical estimation task did not rely on an evaluation of the time elapsed (Whalen, Gallistel & Gelman, 1999). Thirdly, the current anatomical precision of TMS does not allow a perfect localisation of the stimulated area and one cannot safely conclude that exactly the same areas were stimulated in all the reported studies. Whether numerical and temporal

processes do or do not share the same mechanisms and the same neuroanatomical substrate in the parietal cortex is thus still an open question.

One way to identify the specificities and commonalities of two processes is to look at possible mutual interference effects in Stroop or dual-task paradigms. On the one hand, several studies have manipulated the temporal characteristics (e.g., duration of presentation of stimuli, stimulus onset asynchrony) by using masks or a sequential mode in a classic colour-word Stroop task and have shown a decrease in the interference effect proportional to the stimulus onset asynchrony, with a peak around 50 ms pre-exposure of the word (e.g., La Heij, van der Heijden & Plooij, 2001). The temporal dimension was, however, only indirectly approached, and to date, only one study using a Stroop design has really integrated duration as a variable of interest in an auditory task. In this experiment the words *fast* and *slow* were pronounced slowly or quickly according to condition (congruent or incongruent; Morgan & Brandt, 1989); here, duration corresponded to a psychoacoustic attribute of the word. This study did not show a significant difference between the two conditions, which suggested that duration did not interfere with linguistic processing. On the other hand, dual-task paradigms have shown that duration estimation is affected by various types of concurrent tasks (visual search, pursuit rotor tracking and mental arithmetic; Brown, 1997).[6] More generally, filled intervals are perceived as longer than empty intervals, both in the auditory and the visual modalities (e.g., Gibbons & Rammsayer, 2004; Grondin, 1993). Finally, a recent study in children showed numerosity-duration interference effects in a bisection task of a series of flashed dots (Droit-Volet et al., 2003).

How the estimation of time may interfere with other cognitive processes is thus still largely unknown. In the present study, we used a Stroop task to assess the presence of possible effects of facilitation and/or interference between numerical and temporal dimensions. Participants had to compare either the numerosity or the total duration of two successive series

[6] Note, however, that only the mental arithmetic task was impaired by the temporal task, perhaps because both tasks draw on the same pool of executive functions (Brown, 1997).

of visually flashing dots. To avoid as far as possible potential explicit or implicit counting strategies, short duration (ranging from 1200 ms to 2100 ms) and non-subitisable numerosities (from 5 to 9 dots) were used. If the same representational mechanism underlies duration and numerosity processing, then a symmetric effect of interference or facilitation should be observed: the comparison of durations should be influenced by the irrelevant numerical dimension of stimuli and, conversely, the comparison of numerosities should be subject to the influence of the temporal dimension. On the other hand, if the two processes are independent, no mutual effect of interference/facilitation should be observed. Finally, an asymmetric effect of interference/facilitation would signal a faster or more efficient mandatory processing of one of the two dimensions.

2. Methods

2.1 Participants

Thirty volunteers (3 left-handed, 6 males, mean age: 22 ± 1.4 years) participated in this study; fifteen participants completed the numerosity comparison task and fifteen completed the duration comparison task.

2.2 Tasks and stimuli

The experiment was composed of two distinct tasks: a numerosity comparison and a duration comparison of two successive series - constituting a pair or a stimulus - of visually flashing dots. For each task, three types of pairs were constructed: in *congruent pairs*, the series with more dots lasted longer; in *incongruent pairs*, the series with fewer dots lasted longer; and in *neutral pairs*, the numerosity was fixed (6 dots) and the total duration of the series varied in the comparison of duration task, whereas the duration was fixed (1500 ms) and the number of dots varied in the numerosity comparison task. For the congruent and incongruent conditions, the same set of stimuli was used in the two tasks.

All series were composed of black dots (diameter: 3.5 cm) and were constructed using nonperiodic signals so that temporal ratios did not constitute a potential confounding variable and rhythm biases and pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; see Appendix 2.1 for details). The total duration of the series (i.e., the duration of the dots/events plus the interdot/event intervals) ranged from 1200 to 2100 ms and the numerosities ranged from 5 to 9 dots (i.e., not subitizable but below 10). The durations of each dot/event (e_j) and the interdot/event intervals (i_j) were both variable (between 50 and 300 ms); to avoid pattern recognition, each series involved at least one e_j and one i_j of 50 ms and one longer than 200 ms, and each series began and finished with an i_j of 50 ms (Figure 2.1). Pairs of series were chosen to constitute two distances: a *large* distance (3 dots for numerosity, that is, pairs 5-8 and 6-9; 600 ms for duration, that is, pairs 1200-1800 and 1500-2100) and a *small* distance (1 dot for numerosity, that is, pairs 5-6 and 8-9; 300 ms for duration, that is pairs 1200-1500 and 1800-2100). The order of presentation of the two series within the pairs varied: half the pairs began with the shorter/smaller series (S-L) and the other half with the longer/larger (L-S).

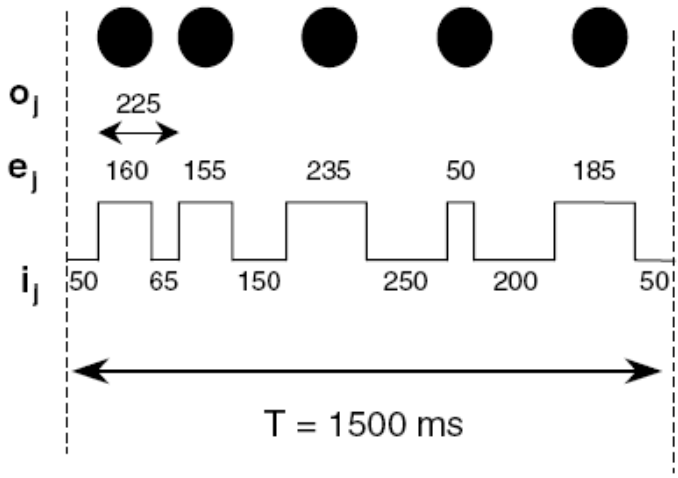

Figure 2.1: Temporal attributes of the stimuli shown on an example of non-periodic series with five dots and a total duration of 1500 ms (T = total signal duration; oj = event onset duration; ej = event duration; ij = interevent duration; see Appendix 1.1 for details).

2.3 Experimental procedure

A Macintosh computer interfaced with a 17" AV screen controlled stimuli presentation and data collection. The viewing distance was approximately 50 cm. At the beginning of each trial, a white rectangle (9.5 cm x 16 cm) was presented on a black background and a first series of dots was flashed in its centre for a given duration, after which the rectangle disappeared and was replaced by a black screen for 1000 ms. Then a new rectangle appeared and a second series of dots was flashed, after which the rectangle disappeared and was again followed by a black screen for a period of up to 1500 ms during which the participants could answer. As soon as the answer was given, the next trial started. Each task was composed of 8 blocks of 24 trials; the three types of pairs were mixed and randomised within each block. A practice block was administered first, but was not included in the analyses.

Each participant was assigned randomly to one comparison task. In the numerosity comparison task, the participants had to decide which series contained more dots by pressing one of two keys on the numerical pad (key *1* with the right index finger for the first series, key *3* with the right ring finger for the second series). In the duration comparison, they had to decide which series lasted longer from the appearance of the first to the last dots of the series, with the same key presses. The instructions clearly requested participants to focus on one of the two dimensions and did not mention the other one.

4. Results

Firstly, a global analysis was carried out on both tasks to look for the possible presence of interference and/or facilitation effects. Secondly, separate analyses were run for the congruent and incongruent conditions of each task in order to test the order and distance effects. In this analysis, the *relevant distance* was that of the dimension that was to be explicitly processed (e.g., the numerical distance in the numerosity comparison) and the *irrelevant distance* was the

distance of the dimension that was not to be explicitly processed (e.g., the duration distance in the numerosity comparison).

4.1. Interference and facilitation effects

An analysis of variance (ANOVA) was performed on the response latencies of correct answers with Task (numerosity *vs.* duration) as a between-subject variable and Condition (congruent, incongruent *vs.* neutral pairs) as a within-subject variable. There was no difference between tasks (mean latencies for duration: 529 ± 98 ms, for numerosity: 485 ± 80 ms; $F(1,28)=2.01$, ns). A significant main effect was found for Condition (mean latencies for congruent: 499 ± 80 ms, incongruent: 528 ± 106 ms, neutral: 494 ± 86 ms; $F(2,27) = 7.79$, $p<.002$). Post-hoc paired-sample *t*-tests indicated that the incongruent condition differed significantly from the congruent and neutral conditions (both $p<.001$). There was also a significant interaction between condition and task ($F(2,27)=8.331$, $p<.002$). Separate ANOVAs for the duration and numerosity tasks with Condition as within-subject variable revealed a main effect of Condition in the duration task ($F(2,13)=13.628$, $p=.001$): the congruent and neutral conditions were answered faster than the incongruent one in the duration task (mean latencies for congruent: 503 ± 81 ms, incongruent: 575 ± 108 ms, neutral: 508 ± 91 ms), whereas no effect was observed in the numerosity task (mean latencies for congruent: 495 ± 82 ms, incongruent: 480 ± 82 ms, neutral: 479 ± 81 ms; $F(2,13)=0.832$, ns; Figure 2.2). It is worth noting that the neutral conditions did not differ significantly (mean latencies for neutral duration: 508 ± 91 ms, neutral numerosity: 480 ± 81 ms; $t(14)=1.828$, $p=.089$). To ensure that this marginal tendency for the numerosity judgement to be slightly faster did not mask a possible (in)congruency effect of duration, two complementary analyses were carried out in the numerosity task. Firstly, participants were divided into two groups according to their mean response latency (fast: 407 ± 24 ms, slow: 561 ± 57 ms) in the neutral condition. An ANOVA again showed no main effect of Condition ($F(2,9)=0.224$, ns) and, most importantly, no Group by Condition interaction ($F(2,9)=0.661$, ns): there was thus no

(in)congruency effect of duration even in the slow group in which participants were slower than in the duration task. Secondly, to test for any specific task-related processing, fast and slow trials were distinguished for each subject. This ANOVA showed no main effect of Condition ($F(2,13)=0.085$, ns) and, no Speed of Trials by Condition interaction ($F(2,13)=1.145$, ns). These complementary analyses thus confirm the absence of an interference effect of duration on the numerosity judgement, whatever the speed of processing.

A similar ANOVA on error rates revealed no differences between tasks (mean percentage of errors for duration: 17.3 ± 9.1, for numerosity: 17 ± 7.4; $F(1,28)=0.017$, ns), but a main effect of condition (mean percentage of errors for congruent: 13.1 ± 5.8, incongruent: 21.5 ± 9.9, neutral: 16.8 ± 6.5; $F(2,27)=9.214$, $p=.001$) and a significant interaction between task and condition ($F(2,27)=6.827$, $p=.004$): the three conditions differed in the duration task (mean percentage of errors for congruent: 10.1 ± 3.4, incongruent: 25.6 ± 9.3 and neutral: 16.0 ± 5.8; $F(2,13)=23.7$, $p<.001$) but not in the numerosity task (mean percentage of errors for congruent: 16.15 ± 6.3, incongruent: 17.4 ± 9.0 and neutral: 17.5 ± 7.2; $F(2,13)=0.213$, ns). In the duration task, all the conditions differed significantly from each other (congruent-incongruent: $p< .001$; congruent-neutral: $p< .003$; incongruent-neutral: $p<.001$; Figure 2.2).

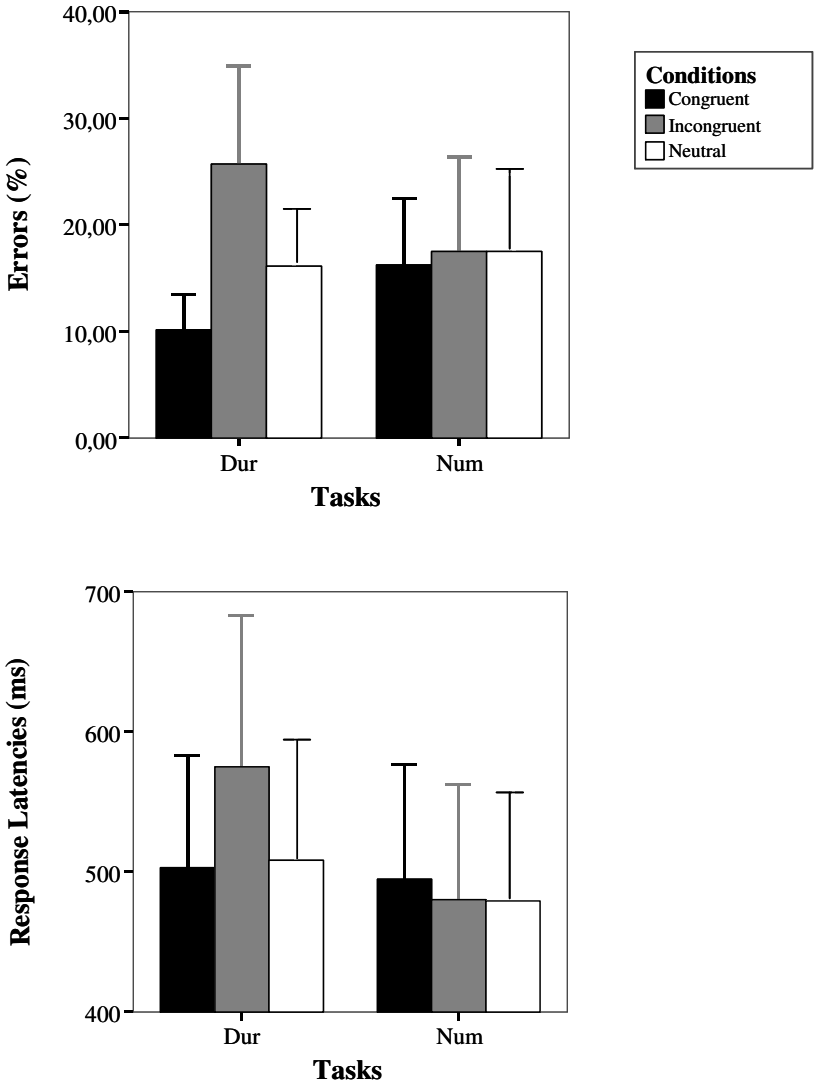

Figure 2.2: Mean percentage of errors and response latency in ms for duration and numerosity tasks as a function of condition (congruent, incongruent, or neutral). Error bars indicate the standard errors of the mean.

4.2. Relevant and irrelevant distance effects

A second analysis was performed on the response latencies of correct answers with Task (duration vs. numerosity) as between-subject variable, and Condition (congruent *vs.* incongruent)[7], Relevant distance (large *vs.* small) and Irrelevant distance (large *vs.* small) as

[7] The neutral condition was not included in this analysis as it was impossible to integrate all the levels of the distance variables.

within-subject variables[8]. There was a significant main effect of Condition ($F(1,28)=6.57$, $p<.02$) that interacted with Task ($F(1,28)=15.15$, $p<.001$): the congruent condition was answered faster than the incongruent one in the duration task but not in the numerosity task (see above). A main effect of Relevant distance was also found: the large distance was answered faster than the small one (mean latencies for large distance: 475 ± 118 ms, small distance: 552 ± 114 ms; $F(1,28)=40.811$, $p<.001$). Finally, there was also a statistically marginal interaction between Condition and Relevant distance ($F(1,28)=3.158$, $p=.086$): there was no difference between congruent and incongruent conditions for large distances whereas there was a significant difference for the small distance (congruent was faster than incongruent). The Irrelevant distance had no significant main effect or interaction with the other variables; the other main effects and interactions were also not significant.

The same ANOVA performed on the mean percentage of errors revealed that the main effects of Condition (mean percentage of errors for congruent: 13.1 ± 5.8, incongruent: 21.5 ± 9.9; $F(1,28)=19.03$, $p<.001$), Relevant distance (mean percentage of errors for large distance: 9.6 ± 10.1, small distance: 25 ± 14.1; $F(1,28)=166.396$, $p<.001$), and Irrelevant distance (mean percentage of errors for large distance: 18.5 ± 15.8, small distance: 16.1 ± 12.9; $F(1,28)=4.483$, $p=.043$). Condition and Task interacted ($F(1,28)=13.78$, $p<.001$), in that the congruent condition produced fewer errors than the incongruent one in the duration task but not in the numerosity task (see above). There was also a significant interaction between Relevant distance and Task ($F(1,28)=7.115$, $p<.02$). With large Relevant distance participants made more errors during the duration task, whereas there was no difference between large and small relevant distance in the numerosity task. Moreover, a significant triple interaction between Condition, Relevant distance

[8] In a separate analysis, the order of presentation of the series (short-long vs. long-short) was introduced as a supplementary within-subject variable. A main effect of order was revealed for the latencies (mean latencies for short-long = 462 ± 15 ms, for long-short = 564 ± 17 ms; $F(1,28)=95.755$, $p<.000$). This effect suggests that the participants could anticipate the correct answer only when the short series was presented first. This variable entered into some interactions but, as it never changed the direction of the main effects of other factors, it was not included in the main analysis.

and Task was found ($F(1,28)=6.006$, $p<.03$): in both tasks, small and large distances differed but this difference was smaller in the congruent conditions of the duration task, and the congruent conditions differed from the incongruent ones only on the duration task (Figure 2.3).

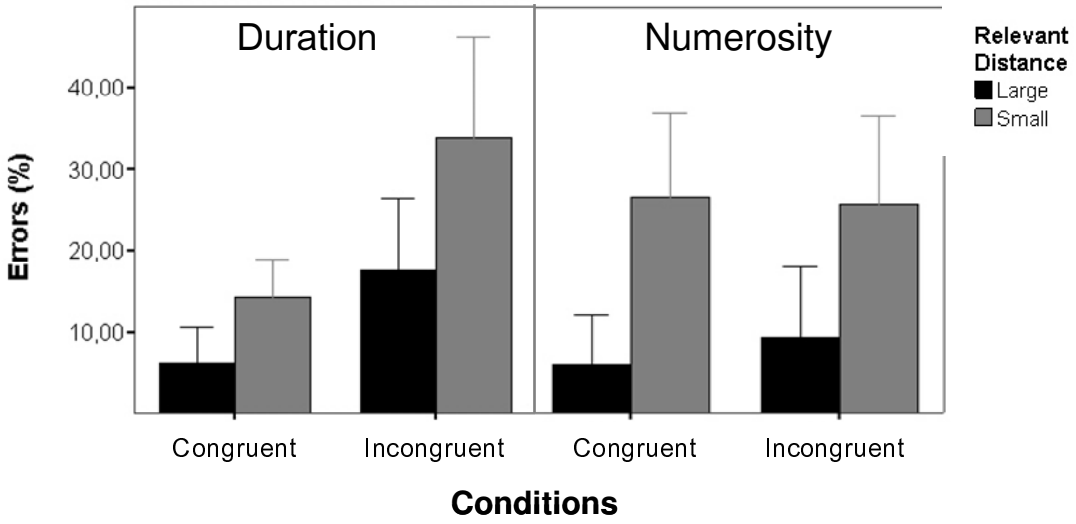

Figure 2.3: Mean percentage of errors for duration and numerosity tasks as a function of condition and relevant distance (for numerosity and duration, respectively: Large = distance 3 and difference 600 ms, Small = distance 1 and difference 300 ms for numerosity and duration, respectively). Error bars indicate the standard errors of the mean.

There was also a marginally significant interaction between Condition and Irrelevant distance ($F(1,28)=3.298$, $p=.08$): in the incongruent condition, subjects made more errors when the irrelevant distance was large whereas there was no difference between large and small distance in the congruent condition. Finally, another statistically marginal interaction between Irrelevant distance and Task was observed ($F(1,28)=4.11$, $p=.052$). A post-hoc paired *t*-test showed that large and small Irrelevant distances differed on the numerosity task only (the large irrelevant distance producing more errors than the small distance).

5. Discussion

The aim of the present study was to investigate the relationship between numerosity and duration processing with a Stroop design and to test whether they share the same mechanisms.

We will first summarise the major findings of this study, and then discuss how they improve our understanding of the mental processing of numerosity and duration.

5.1. Interference/facilitation and distance effects

Firstly, the results showed that in the range of selected durations and numerosities, the duration and numerosity judgments were globally of similar complexity with performance being equally fast and accurate on both tasks. The differences observed are therefore probably not related to differences in attentional or difficulty demands across tasks. In the duration comparison, there was a clear interference effect of numerical cues on response latencies (incongruent slower than neutral and congruent), and both facilitation and interference effects on error rates (fewer and more errors in the congruent and incongruent conditions respectively, compared to the neutral condition). On the other hand, in the numerosity comparison task, there was no difference between the three conditions (congruent, incongruent and neutral) either on responses latencies or on error rates, suggesting that the temporal cues did not influence the numerosity judgments.

Secondly, a classical effect of the relevant distances (e.g., Moyer & Landauer, 1967) was observed in both tasks: the closer the numerosities, the longer and the more error-prone the judgments in the numerosity comparison; the closer the durations, the longer and the more error-prone the judgments in the duration comparison. This effect shows that the participants actually performed the comparisons using the appropriate dimension (i.e., numerosity in the numerosity comparison, duration in the duration comparison). Moreover, the interaction between the pertinent distance and the condition for latencies shows that the incongruent information from the other dimension only interfered for the small distance; that is, when the decision based on the relevant distance was slower and thus possibly more difficult. For the large distance, there was no difference between congruent and incongruent conditions. For error rates, this was true for the duration task only: in the numerosity condition, there was no difference between

congruent and incongruent condition, confirming again that duration cues did not affect the numerosity judgment.

This conclusion may, however, be qualified by the marginal interactions involving the irrelevant distance on the error rates. Surprisingly, there was no difference between small and large irrelevant (numerical) distances in the duration task but there was a difference between small and large irrelevant (temporal) distances in the numerosity task, with large distances leading to more errors. This can be explained by considering the pattern of the nonsignificant interaction between conditions, irrelevant distance and tasks. The absence of an effect in the duration task was in fact due to averaging over the expected facilitation and interfering effects of the irrelevant (numerical) distances in the congruent and incongruent conditions respectively. On the other hand, in the numerosity task, the irrelevant (temporal) distances did not modulate the error rates differentially in the congruent and incongruent conditions but rather led to a global - perhaps attentional - interference effect in both conditions. Thus, although these marginal interactions suggest that temporal cues have some weak effect on numerosity judgments, they do not seem to correspond to real interactions between duration cues on numerosity judgments.

5.2. Mandatory processing of numerosity but not duration?

The interference effect of numerosity found in the present study using series of dots extends previous results using symbolic material. Several behavioural studies have shown the automatic activation of magnitude information with Arabic or verbal numerals in Stroop tasks (Algom, Dekel & Pansky, 1996; Henik & Tzelgov, 1982; Tzelgov, Meyer & Henik, 1992) or simply in tasks where the numerical magnitude is not the key dimension to be processed (e.g., identity judgements: Dehaene & Akhavein, 1995; phoneme monitoring: Fias, Brysbaert, Geypens & d'Ydewalle, 1996; orientation judgements: Fias, Lauwereyns & Lammertyn, 2001). These results supported the idea of involuntary and irrepressible access from Arabic numerals to the representation of numerical quantities. In adults, such automatic access to magnitude from non

symbolic material had previously been suggested by a priming task (Koechlin, Naccache, Block & Dehaene, 1999) and a recent study using an adaptation paradigm (Piazza et al., 2004) with identity (same-different) or numerosity (smaller-larger) judgments of simultaneously presented patterns of dots, requiring an explicit or implicit processing of numerosity. The present study extends the demonstration of the automatic activation of magnitude to non symbolic sequentially presented material: the numerosity cues strongly interfered with the judgement of duration, and, most critically, in a context where numerosity did not have to be processed to carry out the task.

As performance did not differ globally across tasks, the asymmetrical interference effect observed in the present study may reflect a difference in the mandatory processing of numerosity and duration: whereas numerosity processing appears to take place automatically, duration processing is not automatic - or, at least, not in a way which leads to strong interference effects. Similar results have recently been observed in adults and 5-to-8-year-old children during a bisection task of series of flashed dots displayed for 2 to 8 seconds (Droit-Volet et al., 2003). Numerosity interfered with performance in the duration condition, indicating that children and adults did not process these two dimensions independently when asked to explicitly process duration; however duration did not interfere with numerical discrimination in the numerosity condition for either age group. In that study, the asymmetry in interference was interpreted in terms of attentional load: it was considered easier to ignore duration than numerosity because the former requires more attentional resources. This was especially true for the youngest children, who could dissociate duration and numerosity in the duration task only when allowed to use a counting strategy that reduced the interfering effect of numerosity. In the present experiment, there is no behavioural evidence of a differential attentional demand between the two tasks. Moreover, the very short durations we used probably made a counting strategy very difficult, if not impossible, to apply. This may explain why numerosity still interfered, even with adult participants. Finally, as suggested by an anonymous reviewer, explicit judgements on

numerosity are frequent, whereas judgements on duration are generally made implicitly and prospectively rather than retrospectively. Short durations, such as those used in this experiment, are mainly relevant for anticipatory or programming actions, but not for comparative judgements. This lack of expertise in explicit comparative judgements of short durations may be one of the reasons underlying this asymmetry.

5.3. A common mechanism for numerosity and duration processing?

The observed asymmetry of interference does not allow us to draw strong conclusions concerning a possible common mechanism for numerosity and duration processing as postulated by some authors (Meck & Church, 1983; Walsh, 2003). This asymmetry could arise with or without such a common mechanism, simply as a consequence of a faster and or/more automatic processing of numerosity. As the neutral conditions of the two tasks did not differ significantly, the hypothesis of faster processing can probably be rejected. Therefore, the fact that both estimation processes take place simultaneously, as suggested by the present results, challenges the idea of a single accumulator underlying the two estimation processes, unless the accumulator works simultaneously in its two operative modes. Alternatively, several accumulators could work in parallel (e.g., numerosity and duration could be processed independently by two different accumulators before converging on a common response-selection system). Caution should be exercised with this conclusion given the marginal trend for numerosity judgements to be slightly faster. However, the absence of an (in)congruency effect of duration in the slowest group of subjects and also in the slowest trials indicates that duration cues had no effect, even with slow numerosity judgements. Neuroimaging data would help resolve the issue. Indeed, it has been suggested that the interference from irrelevant information would be stronger if the relevant and irrelevant dimensions rely on the same neuronal structures (Fias et al., 2001), and that a common functional mechanism should lead to common brain activations in the same cerebral structures, even if one of the two processes is faster and/or more automatic. In a positron emission

tomography study we carried out recently, preliminary analyses revealed no common activation in the parietal cortex in numerosity and duration of flashed dots comparison tasks (Pesenti, Thioux, Dormal, De Volder & Seron, 2003). These anatomo-functional results must however be replicated before a firm conclusion can be drawn.

6. Conclusions

The present study was aimed at testing the existence of a possible common mechanism for duration and numerosity processing. Comparisons of the duration and numerosity of series of flashing dots were tested in a Stroop design in which the two dimensions were controlled to create congruent, incongruent and neutral pairs. This allowed us to investigate whether and how the temporal cues interfered with the processing of numerosity, and inversely whether and how the numerical cues interfered with duration processing. Results show that numerical cues interfered with duration processing (they facilitated duration processing when numerosity and duration were congruent, but interfered with it when they were incongruent), whereas temporal cues did not affect numerosity processing. These findings extend the idea of automatic access to magnitude to non symbolic sequentially presented material, and reflect a probable difference in the processing of numerosity and duration.

Appendix 2.1: Control of temporal and pattern ratios.

Breukelaar and Dalrymple-Alford (1998) pointed out that using classical periodic signals (i.e., signals with constant event-interval durations) introduces two potential biases in number/duration discrimination tasks. Firstly, periodic event sequences allow discriminations to be based on uncontrolled and unintended temporal attributes of the event sequence, confounded with numerosity. Indeed, when a fixed number of identical events occur periodically, the ratios of the intervals between event onset (o_j), event duration (e_j), and inter-event duration

(i_j) to the total duration (t) remain constant (respectively, $o_j{:}t$, $e_j{:}t$, and $i_j{:}t$; see Figure 2.1), irrespective of the total signal duration. This has been called the *temporal ratio*.

This temporal ratio always covaries with the number of events even when duration and numerosity are not confounded (by holding constant one of the two dimensions while the other varies). Secondly, when only a few sequence patterns are used, participants may learn to respond to a signal by matching it to a specific standard stored in memory. The solution to both problems is to use unique nonperiodic signals: in every trial, the temporal pattern for each numerosity - or duration - relevant signal is randomly generated by adjusting the o_j's, e_j 's and i_j's. The *ratio deviation score* (DS ratio) provides a measure of deviation in terms of the $o_j{:}t$ ratio, and a *pattern deviation score* (DS pattern) provides a measure of deviation in terms of the signal patterns. Both scores can be derived from the following formula:

$$DS = \sqrt{\sum_{j=1}^{j=n} (D - d_j)^2} \qquad [1]$$

For the DS ratio, D is the event duration of the corresponding periodic signal, dj is the current event onset, and n the number of events. For the DS pattern, D is the event or interval duration of the corresponding periodic signal, while d_j is the current event or interval duration (so that j is odd for events and even for intervals), and n is the total number of events and intervals. The more distant the ratios are from 0, the less the numerosity-duration confounding and the pattern regularity. For example, say a signal is composed of the following succession of five events and five intervals for a total duration of 1500 ms: event(e)$_1$ = 160 ms, interval(i)$_1$ = 65 ms, e_2= 155 ms, i_2 = 150 ms, e_3= 235 ms, i_3 = 250 ms, e_4= 50 ms, i_4 = 200 ms, e_5= 185 ms, and i_5 = 50 ms. The various ratios derived from [1] are as follows:

n: 5;
D (for ratio): (1500/5) = 300;
D (for pattern): (300/2) = 150;

DS ratio:

$$= \sqrt{(300-(160+65))^2+(300-(155+150))^2+(300-(235+250))^2+(300-(50+200))^2+(300-(185+50))^2}$$

= 216;

DS pattern:

$$= \sqrt{(150-160)^2+(150-65)^2+(150-155)^2+\ldots+(150-50)^2}$$

= 220.

All series of items are equated, so that the mean DS ratio for the five items of each category of series varies between 243 and 244. The DS pattern is always maintained above 150. Moreover, within each item, the two series have exactly the same DS ratio.

Chapitre 3

Common contributions of the right intraparietal sulcus in duration and numerosity processing

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Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal, Dormal, & Pesenti (en préparation).

1. Abstract

Separate investigations of the cerebral substrates of numerosity and duration processing have revealed some similarities in their respective activation profiles, especially in parietal and frontal areas. Since the 80's, a functional magnitude representation for numerosity and duration being operative through a common accumulator mechanism has been proposed. However, the precise cerebral implementation of this accumulator model has not yet been directly assessed. Here, functional magnetic resonance imaging was used to examine the common neural correlates of both numerosity and duration processing. Participants had to categorize (1) the numerosity of flashed dot sequences or (2) the duration of single dot displays. The conjunction results reveal a large right lateralized fronto-parietal network commonly activated in numerosity and duration processing. We propose that the right IPS might underlie a common magnitude representation/system, corresponding possibly to the encoding and accumulation stages of the accumulator model, whereas frontal regions might be involved in subsequent working memory storage and decision making processes.

2. Introduction

Number and time are both fundamental dimensions provided by the environment based on which individuals constantly regulate their learning and behavior in order to adapt to the external world. Existing literature provides strong evidence showing that abilities to quantify numerosities (i.e., number of elements in a collection) and temporal intervals are shared by both human beings and animals and develop early in infancy. In the early 80's, Meck & Church (1983) introduced the accumulator model, a functional mechanism underlying both numerical and temporal estimation processes and capable of representing these dimensions under on a common representational format. In this model, a pacemaker corresponding to a clock or a counter initially sends pulses to an accumulator either each time an event is encountered or at a given frequency. Than, the pulses are summed in the accumulator and stored in working memory in order to be compared to previously memorized numerical and temporal magnitudes. Finally, the decision is made on the basis of the comparison between the values stored in working memory and the values stored in reference memory. Recently, the hypothesis of a common functional mechanism shared by numerical and temporal processes was reintegrated within a theory of generalized magnitude (ATOM), postulating that inferior parietal cortex hosts a system underlying the representation of different types of quantifiable dimensions such as number, time and space on common metrics, tightly linking them together in order to guide behavior (Bueti & Walsh, 2009; Walsh, 2003).

Such a shared mechanism and cerebral substrate for numerical and temporal processes might explain the close links that have been reported in behavioural protocols. Firstly, psychophysical data in both numerical and temporal estimation tasks have revealed very similar response function distributions with Weber's signature (i.e., the precision of magnitude estimation decreases linearly as the size of the to be estimated magnitude increases) as well as classical distance (i.e., the ability to discriminate two magnitudes increases as the distance

between them grows) and size effects (i.e., when the distance between two magnitudes is kept constant, the ability to discriminate them increases as their sizes decrease) (Cohen Kadosh et al., 2008; Meck & Church, 1983; Moyer & Landauer, 1987). By manipulating numerosity and presentation time of patterns of symbolic and non symbolic stimuli, several studies demonstrated that more stimuli are generally perceived as lasting longer (Cappelletti et al., 2009; Dormal, Seron & Pesenti, 2006; Droit-Volet et al., 2003; Roitman et al., 2007; Xuan et al., 2007). Moreover, studies searching for direct functional links between these two dimensions have consistently reported unidirectional interference of numerosity on duration judgments. This has been interpreted in terms of difference in the mandatory processing of numerosity and duration, suggesting higher automaticity in numerosity processing (Dormal et al., 2006). Although behavioural studies support the existence of strong numerical-temporal interactions, they fail to provide firm conclusions regarding their neuroanatomical correlates.

At the neuroanatomical level, numerosity and duration estimation processes have been investigated mainly separately. Neuroimaging and neuropsychological studies have brought converging evidence towards an involvement of parietal cortex in both type of magnitude processing. On the one hand, the crucial role of parietal cortex around the intraparietal sulcus in numerical cognition is widely accepted in brain imaging studies with healthy participants (Dehaene et al., 2003). More specifically regarding non symbolic numerical material, bilateral activation of the intraparietal sulcus have been shown in response to numerosity changes in passively presented patterns of geometrical shapes such as dots and squares (Cantlon et al., 2006; Piazza et al., 2004; 2007). In line with this, bilateral fronto-parietal activations including the intraparietal sulci were identified during explicit comparison of visual collections (Ansari & Dhital, 2006; Castelli et al., 2006; Dormal & Pesenti, 2009), while a similar but strictly right-lateralized network was reported during a comparison task of sequentially presented visual and auditory sequences (Piazza et al., 2006). On the other hand, brain imaging studies investigating neural

correlates of duration processing suggest the implication of an extended cerebral circuit including the basal ganglia, the supplementary motor area and the cerebellum, as well as a fronto-parietal network mainly in the right hemisphere (e.g., Belin et al., 2002; Ferrandez et al., 2003; Jueptner et al., 1995; Lewis & Miall, 2003a; Lewis & Miall, 2003b; Macar et al., 2002; Pouthas et al., 2005; Rao et al., 2001). Inferior parietal cortex activity, sometimes around the intraparietal sulcus, has been consistently reported in many of these studies during time estimation tasks performed in the milliseconds to second range, both in visual and auditory modalities (Belin et al., 2002; Ferrandez et al., 2003; Lewis & Miall, 2003b; Pouthas et al., 2005; Rao et al., 2001). Finally, while neuropsychological findings have consistently demonstrated the crucial role of parietal cortex in numerical cognition (Cipolotti et al., 1991; Dehaene & Cohen, 1995; Lemer et al., 2003; Polk et al., 2001; Warrington & James, 1967), a few lesional studies have revealed temporal perception deficits following parietal damage in brain-lesioned patients (Cappelletti et al., 2009; Coslett, Shenton, Dyer & Wiener, 2009; Harrington et al., 1998). Moreover, similar findings have been reported in separate studies involving either numerical or temporal bisection tasks in hemineglect patients with right parietal damage (Oliveri et al., 2009; Zorzi et al., 2002; Zorzi et al., 2006). For instance, when asked to report the middle point of either a numerical or a temporal interval, patients with hemineglect tend to overestimate both the middle point between two numerical values and the middle point of a temporal interval, mirroring the performances that have largely been documented in line bisection tasks. Interestingly, similar biases can be induced in healthy participants by applying transcranial magnetic stimulation on the right posterior parietal cortex (Göbel, Calabria, Farnè & Rossetti, 2006; Oliveri et al., 2009). Other transcranial magnetic stimulation studies have revealed drops in performances during either numerosity (Cappelletti et al., 2007; Dormal, Andres & Pesenti, 2008) or duration estimation tasks (Alexander et al., 2005; Bueti et al., 2008) following stimulation of the left intraparietal sulcus and the right posterior parietal cortex, respectively.

To sum up, various pieces of evidence from different and specific research fields on the neuroanatomical correlates of numerosity and duration processing converge towards a crucial role of parietal regions in both processes. While such separate evidence tends to be in agreement with the existence of a generalized magnitude system underlain by a common cerebral substrate in the parietal cortex, within-subject data are needed to state whether the parietal regions involved are identical across numerical and temporal judgment tasks.

Using fMRI, the main goal of the present study was to provide such data by directly comparing the patterns of neural activation during numerosity and duration categorization. Moreover, highlighting the cerebral network common to both types of processes, we provide for the first time the possible neuroanatomical implementation of the accumulator model (Meck & Church, 1983). For this purpose, participants were scanned while performing two tasks: a numerosity categorization of sequences of dots (hereafter, NUM for Numerosity) and a duration categorization of single dots (hereafter, DUR for Duration). In the NUM task, participants had to categorize each sequences as containing “few” or “many” dots; in the DUR task they had to categorize each dot as being presented for a “short” or a “long” time. If the same representational mechanisms and medium underlie duration and numerosity processing, then common activations should be found, possibly in areas around the IPS.

3. Methods

3.1 Participants

Fifteen healthy male adults (mean age: 21 ± 2.3 years) took part in this experiment after giving their written consent. All participants were right-handed as attested by the Edinburgh inventory questionnaire (Oldfield, 1971), had no history of neurological or psychiatric disorders, had normal or corrected-to-normal vision, and were unaware of the purpose of the study. The experiment was non-invasive and was performed in accordance with the ethical standards laid

down in the 1964 Helsinki Declaration; the experimental protocol was approved by the Biomedical Ethical Committee of the Université Catholique de Louvain.

3.2 Tasks and stimuli

Four tasks were used: two experimental categorization tasks and two matched reference tasks, all equated in terms of visual complexity and forced-two-choice button-press decision.

To avoid as much as possible potential explicit or implicit counting strategies, non-subitizable numerosities and short durations were used. Stimuli in the numerosity categorization task were composed of temporal sequences of either 6 or 8 black dots (diameter: 3.5 cm) presented one at a time at the centre of the screen (Figure 3.1). The sequences were constructed using non-periodic signals such that temporal ratios did not constitute a potential confound, and rhythm biases as well as pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; Dormal et al., 2006). The total duration of the sequences was kept constant (1800 ms), while the duration of each dot presentation (*ej*) and the duration of the interdot interval (*ij*) varied randomly from 50 to 270 ms. Stimuli in the duration task corresponded to a single black dot (diameter: 3.5 cm) presented at the centre of the screen for either 600 or 900 ms (Figure 3.1). Stimuli in the reference tasks were identical to those in the experimental categorization tasks except for the fact that the last dot in half of the numerical sequences and the last 100 ms in half of the single dots were filled in red (Figure 3.1).

In the numerosity categorization task, the participants had to decide whether each sequence of dots contained “few” (i.e., 6) or “many” (i.e, 8) dots by pressing a left- or right-hand response button on a response box. In the duration task, they were required to categorize each dot as being presented for a “short” (i.e, 600 ms) or a “long” (i.e, 900 ms) time by using the same two-choice button press decision. In the corresponding reference tasks, participants were asked to report whether the last dot in each sequence or the last 100 ms of each single dot was colored or not.

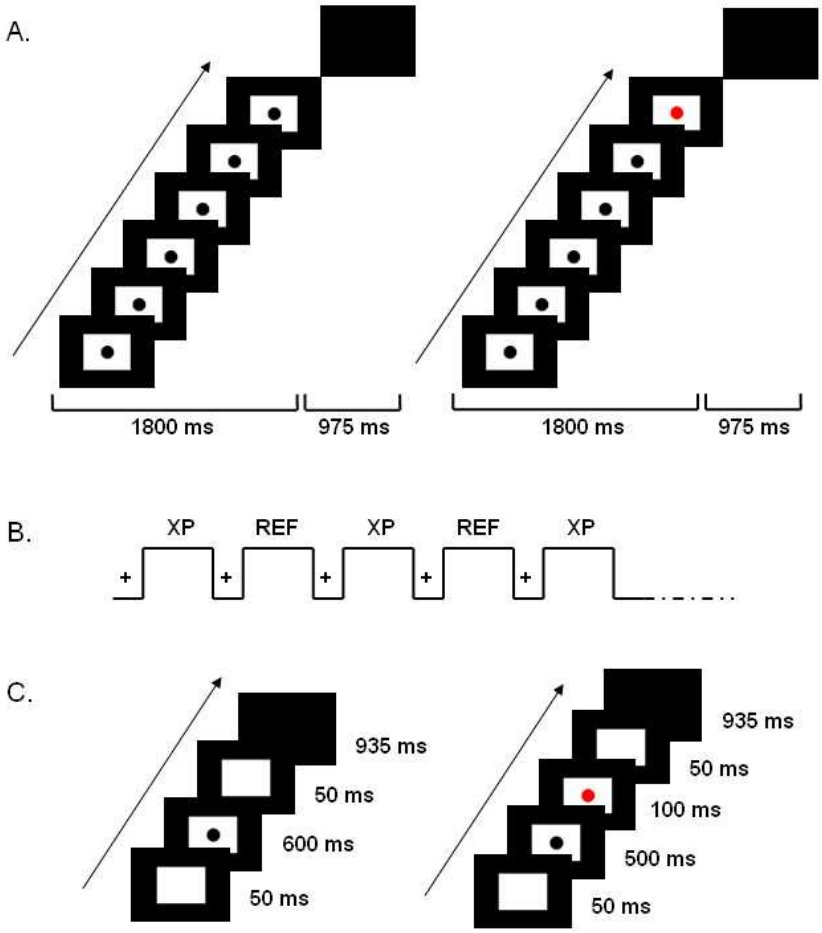

Figure 3.1: Schematic representation of the temporal structure of the experiment**. (A)** Examples of experimental (left) and reference (right) task in the numerosity task: each trial was composed of a stimulus (a sequence of flashed dots) displayed for 1800 ms, and a blank response screen for 975 ms. For the reference task, the last dot of the sequence was either black or red. **(B)** fMRI design. Each run consisted of 10 alternations of a 12.5-sec fixation period (black cross on white background) and a 25-sec activation period. Each activation period corresponded to either an experimental condition or its reference condition. **(C)** Examples of experimental (left) and reference (right) task in the duration task: each trial was composed of a stimulus (one central black dot) displayed for 600 or 900 ms, followed by a blank response screen for 935 ms. For the reference task, the color of the dot turned red during the last 100 ms of half of the trials.

3.3 Experimental design

Prior to the scanning session, participants were trained on all tasks outside the magnet room. For each of the categorization tasks, a training session consisted of a learning block, a training block with feedback, and an example of a four-block fMRI acquisition run. In the learning block, 20 sequences with "few" and "many" dots were presented for the numerosity categorization task, and 20 examples of "short" and "long" dots were presented for the duration

categorization task, while participants were instructed to observe them carefully. The numerosity of the sequences and the duration of presentation of the single dots were never mentioned. During the training block with feedback, stimuli from each category were presented in randomized order and participants were required to categorize each of the sequences as containing "few" or "many" dots and each of the single dots as being "short" or "long" by pressing one of two keys on the numerical pad (key 1 with the right index finger for sequences/single dots categorized as "few *vs.* short" and key 3 with the middle finger for sequences /single dots categorized as "many *vs.* long"). A visual feedback after each trial informed the participant of whether his answer was correct or not. Finally, the participants underwent a four-block run (i.e, two blocks of the experimental task alternating with two blocks of the corresponding reference task) to familiarize them with the fMRI procedure.

In the magnet room, back-projected images were viewed through a tilted mirror mounted on the head coil, and the participants answered by pressing a 2-button response pad with two fingers of their right hand; the projector and the mirror (Silent Vision^{TM} System, Avotec, Inc., <http://www.avotec.org>) and the response pad (Imagilys, <http://www.imagilys.com/>) were compatible with the MRI environment. Stimulus presentation and response recording were controlled with E-Prime (Schneider, Eschman & Zuccolotto, 2002).

Two runs were constructed for the fMRI experiment. One consisted of 5 blocks of the numerosity categorization task alternating with 5 blocks of its reference task, and the other was composed of 5 blocks of the duration categorization task alternating with 5 blocks of its reference task. The blocks lasted for 25 sec and were interleaved with 12.5 sec-fixation periods (Figure 3.1). All participants were administered each run twice, in two counterbalanced orders (i.e, ABBA or BAAB). At the beginning of each run, instructions were reminded and examples of sequences/single dots from each category ("few *vs.* short" and "many *vs.* long") were presented.

3.4 fMRI data acquisition

Functional images were acquired with a 3.0 Tesla magnetic resonance imager and an 8-channel phased array head coil (Achieva, Philips Medical Systems) as series of blood-oxygen-sensitive T2*-weighted echo-planar image volumes (GRE-EPI). Acquisition parameters were as follows: TE = 32 ms, TR = 2500 ms, Flip angle = 90°, Field of view = 220 x 220 mm, slice thickness = 3.5 mm with no interslice gap, SENSE factor (parallel imaging) = 2.5. Each image volume comprised 36 axial slices acquired in an ascending interleaved sequence. High-resolution anatomical images were also acquired for each participant using a T1-weighted 3D turbo fast field echo sequence with an inversion recovery prepulse (150 contiguous axial slices of 1 mm, TE = 4.6 ms, TR = 9.1 ms, Flip angle = 8°, FOV = 220 x 197 mm, voxel size = 0.81 x 0.95 x 1 mm^3, SENSE factor = 1.4). Head movement was limited by foam padding within the head coil and a restraining band across the forehead.

3.5 fMRI data analysis

Data were processed and analyzed using Statistical Parametric Mapping (SPM2, Welcome Department of Cognitive Neurology, London, UK, <http://www.fil.ion.ac.uk/spm>). Functional images were (1) corrected for slice acquisition delays, (2) realigned to the first scan of the first run (closest to the anatomical scan) to correct for within- and between-run motion, (3) coregistered with the anatomical scan, (4) normalized to the MNI template using an affine fourth degree ß-spline interpolation transformation and a voxel size of 2 x 2 x 2 mm^3 after the skull and bones had been removed with a mask based on the individual anatomical images, and (5) spatially smoothed using a 10-mm FWHM Gaussian kernel.

Condition-related changes in regional brain activity were estimated for each participant by a general linear model in which the responses evoked by each condition of interest were modeled by a standard hemodynamic response function. The comparisons of interest were first computed at the individual level to identify the cerebral regions significantly activated by

numerosity and duration processing relative to the fixation periods used as a general baseline (respectively, *[NUM – fix],* and *[DUR – fix]*), and similarly for each reference task. Significant cerebral activations for these tasks were then examined at the group level in random-effect analyses using one-sample *t*-tests and analyses of variance (ANOVA), with the statistical threshold set at $p<.05$ (FWE corrected at the voxel level) and extending to at least 50 contiguous voxels. Given the strong *a priori* hypotheses, activations in the parietal cortices were also screened at lower, uncorrected thresholds. The conjunction (using the Minimum Statistic compared to the Conjunction Null, MS/CN; Nichols, Brett, Andersson, Wager & Poline, 2005) of the two experimental comparisons with their own reference isolated the cerebral activations elicited in common by numerosity and duration categorization.

4. Results

4.1 Behavioural data

Two ANOVAs were performed, one on the response latencies (RLs) of correct answers and another on error rates, with condition (Experimental *vs.* Reference) and task (NUM *vs.* DUR) as within-subject variables. A significant main effect of condition was observed both for RLs ($F(1,14)=7.261$, $p<.02$) and error rates ($F(1,14)=42.263$, $p<.001$). Participants responded faster and made fewer errors overall in the reference (340 ± 58 ms; 2 ± 2%) than in the experimental tasks (371 ± 63 m; 10 ± 6%). No other main effect or interaction was significant.

4.2 Functional data

4.2.1 Numerosity processing

Contrasting the NUM task to its reference revealed the cerebral areas involved in numerosity processing on sequentially presented non symbolic material. A right-lateralized hemispheric activation was identified in the inferior parietal lobule all around the IPS. Areas of activation were also observed in the right middle and inferior frontal gyri, and the right

supplementary motor area (Table 3.1a and Figure 3.2A). A small left superior parietal activation (k=2) also appeared at an uncorrected threshold (p<.003).

4.2.2 Duration processing

Contrasting the DUR task to its reference revealed a large focus of activation in the right middle and superior frontal gyri. Other activation foci were found in the right inferior parietal lobule along the IPS and in the left cerebellum (Table 3.1b and Figure 3.2A). At an uncorrected threshold (p<.005), a small left inferior parietal activation (k=3) was observed.

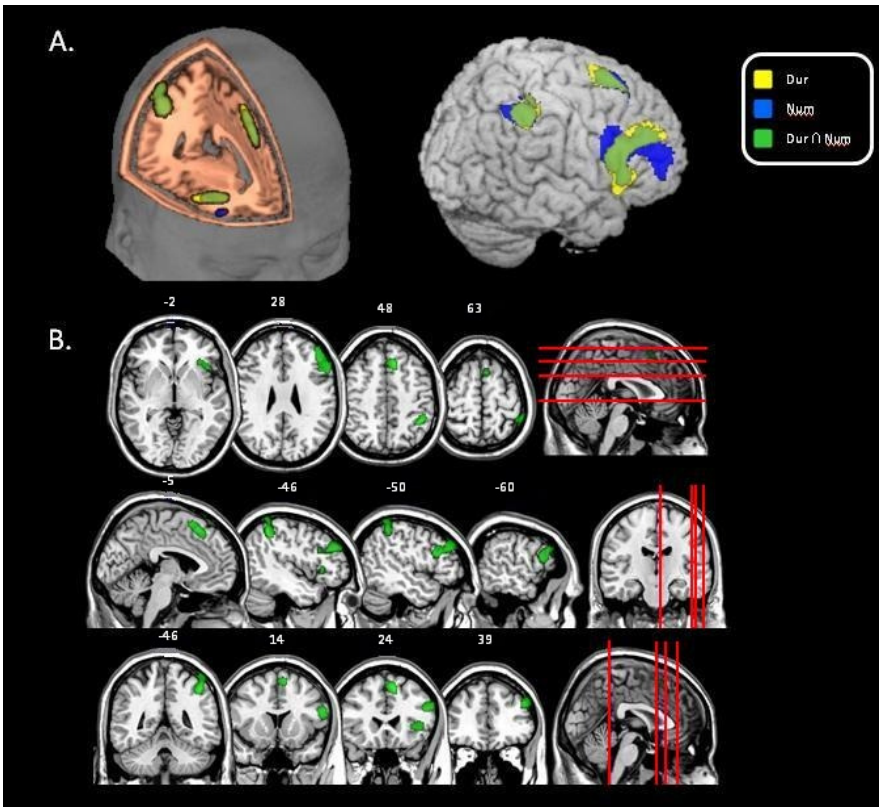

Figure 3.2: **(A)** Brain regions activated specifically and commonly in the two experimental tasks (i.e., Num and Dur) on a 3D reconstructed brain (left panel) and on a glass brain (right panel; in a corrected threshold p<.05). **(B)** Axial, sagital and coronal views of the brain regions showing increased activity in the conjunction analysis. The blue lines in the right external views indicate the planes corresponding to the sagital views (for the upper and lower panels) or to the coronal views (for the middle panel).

4.2.3 Numerosity and duration processing

The conjunction of N and D tasks, each contrasted to its own reference, revealed the areas commonly involved in numerosity and duration processing. Two important activation areas were observed: one spreading in the right frontal lobe and one in the horizontal segment of the IPS (with a local maximum at 44 -46 52; Table 3.1c, Figure 3.2A and B). A left IPS focus also appeared at an uncorrected threshold (p<.005).

4.2.4 Color processing

Contrasting jointly the reference tasks of NUM and DUR to fixation periods revealed the cerebral areas involved in color detection tasks. Only two foci situated in the left and right temporo-occipital junction were activated during the NUM and DUR reference tasks at an uncorrected threshold (p<.001) (Table 3.1d).

Table 3.1: Brain regions showing significant activation for (a) Numerosity (NUM) and (b) Duration (DUR) categorisations each compared to its own reference task (Ref), in the (c) conjunction of the two categorization tasks (NUM and DUR), and (d) for the two reference tasks (RefNUM and RefDUR) compared to fixation.

	Brain regions	*L / R*	*k*	*x*	*y*	*z*	*t-statistic*
a	[NUM-Fix]-[RefNUM-Fix]						
	Middle frontal gyrus	R	1416	50	38	34	8.00*
	Supplementary motor area	R	401	10	22	52	7.91*
	IPS/inferior parietal lobule	R	337	44	-46	50	7.82*
	Inferior frontal gyrus	R	177	40	24	4	6.82*
	Superior parietal lobule	L	2	-40	-52	68	2.97***
b	[DUR-Fix]-[RefDUR-Fix]						
	Middle frontal gyrus	R	1448	50	38	34	8.10*
	Superior frontal gyrus	R	560	10	26	48	8.62*
	IPS/inferior parietal lobule	R	428	44	-46	52	7.91*
	Cerebellum (superior semilunar lobule)	L	63	-38	-64	-32	6.31*
	IPS/inferior parietal lobule	L	3	-46	-42	54	2.72****
c	[DUR-RefDUR] & [NUM -RefNUM]						
	Middle frontal gyrus	R	690	50	38	34	8.00*
	Medial superior frontal gyrus	R	368	8	26	48	7.89*
	IPS/inferior parietal lobule	R	290	44	-46	52	7.71*
	Inferior frontal gyrus	R	176	40	24	4	6.82*
	IPS/inferior parietal lobule	L	69	-40	-48	48	2.27****
d	[RefNUM-Fix] U [RefDUR-Fix]						
	Middle temporal gyrus	L	248	-50	-72	6	3.31**
	Middle temporal gyrus	R	100	46	-64	2	3.00**

L = left hemisphere; R = right hemisphere; k = cluster size (number of voxels); x, y, z = stereotaxic coordinates of peak-height voxels; * = p-values < 0.05 FWE corrected for multiple comparisons; ** = p-values < 0.001 uncorrected; *** = p-values < 0.003 uncorrected; **** = p-values < 0.005 uncorrected.

5. Discussion

Adults, infants and animals process and represent numerosity and time. They approximate the number of elements in a set and the duration of an event, and they use these quantification processes to guide learning and behavior. To account for this strong parallel between time and numerosity estimation, Meck and Church (1983) proposed the existence of a single representational mechanism, namely an accumulator, allowing to represent both dimensions in an analogue way through different operative modes. The recent proposal of a generalized magnitude system widened this accumulator-model to the processing of other magnitude dimensions such as space or weight to account for the existence of a common functional mechanism involved in all estimation processes and underlain by a common cerebral substrate (Walsh, 2003). In agreement with such proposal, many similarities and interaction effects between numerosity and duration estimation processes have been reported at the behavioral level, and separate neuroanatomical investigations on the cerebral areas involved in numerosity and duration estimation have pointed towards the crucial involvement of the parietal cortex in both types of magnitude processing (e.g., Lewis & Miall, 2003a; Piazza et al., 2006). However, so far, the precise cerebral network involved commonly in both magnitude estimation processing had not previously been directly assessed. In the present study, participants had to decide whether a flashed dot sequence contained "few" or "many" elements and whether a single dot display was presented for a "short" or a "long" period of time.

First, a direct contrast for the numerosity categorization task revealed the cerebral network implicated in sequential numerosity processing, namely a right lateralized fronto-parietal network comprising a large portion of the IPS. This network of areas has recently been largely documented (e.g., Castelli et al., 2006; Piazza et al., 2006). During the duration categorization task, activations were found in right frontal and parietal areas and in the left cerebellum, mirroring the activation patterns mainly reported in cognitively-controlled time measurement

tasks (i.e., tasks involving a perceptive judgment on discrete duration around the second; for a recent review, see Lewis & Miall, 2003a).

The major finding of the present study is the highlighting of common cerebral areas recruited for both duration and numerosity processing. Functional data revealed two main regions of activation: a large zone in the right frontal regions, extending from the middle to the superior frontal gyri and a right IPS focus. We speculate that this fronto-parietal network may reflect the functional implementation of the common mechanism allowing to process and represent numerosity and time as mental magnitudes (Gallistel & Gelman, 2000; Meck & Church, 1983). As prefrontal and parietal regions are functionnaly interconnected (Cavada & Goldman-Rakic, 1989; Chafee & Goldman-Rakic, 2000), the parietal activation might uphold an initial process of encoding information as well as continuously accumulating it through functional connections to the frontal cortex that would be more specifically implicated in later stages of magnitude processing such as comparing the perceived values to reference memory and decision making. Electrophysiological studies in monkeys in numerosity and time estimation fit with such a proposal. Firstly, neural populations sensitive to numerosity and time have been recorded in separate studies in different parietal regions and in the prefrontal cortex (For numerosity: Nieder et al., 2002; Nieder & Miller, 2004; For duration: Chiba et al., 2008; Janssen & Shadlen, 2005; Leon & Shadlen, 2003; Oshio et al., 2006; Sakurai et al., 2004). More importantly, differences have been reported in the activity profiles of these selective-neuronal populations depending on their neuroanatomical implementation. For instance, numerosity-coding cells in the IPS of the monkeys have been demonstrated to present shorter latencies than the homologous neural populations located in prefrontal cortex, suggesting the recruitment of a parieto-frontal network for numerosity processing in which numerical information is initially extracted in the IPS and then transmitted to the frontal areas for subsequent processing (Nieder & Miller, 2004). With respect to neural populations underlying time processing, duration sensitive neurons in parietal areas

seem to represent temporal information quantitatively, while prefrontal neurons encode this information in a binary or categorical way (Chiba et al., 2008; Janssen & Shadlen, 2005; Leon & Shadlen, 2003; Oshio et al., 2006; Sakurai et al., 2004). Interestingly, an fMRI study in humans exploring the time course of brain activation during a duration estimation task convincingly evidenced an early right inferior parietal cortex contribution in duration processing, possibly underlying perceptual encoding of information, and a later recruitment of prefrontal cortex, most probably reflecting comparison processes and decision making (Rao et al., 2001). When human participants had to compare sequentially presented numerosities, the similar parietal and frontal areas were both activated, reflecting a fronto-parietal loops knew to be involve in several cognitive processes where the active maintenance of information online is necessary (Piazza et al., 2004). Hence, capitalizing on these findings, we suggest that the common fronto-parietal network found in the present study reflects the recruitment of a mechanism in which numerical and temporal magnitudes are first extracted in the parietal cortex through encoding and accumulation processes and than sent to the frontal regions for subsequent processing.

More specifically within this frontoparietal network, the right intraparietal focus might possibly sustain the common representation of duration and numerosity magnitudes. Indeed, separate neuroanatomical evidence in numerosity and duration processing converge towards this region as the best candidate for the cerebral correlate of a common representational magnitude system, as proposed by Walsh (2003). In line with this hypothesis, a previous fMRI study (Dormal & Pesenti, 2009) exploring cerebral correlates of numerosity and length processing revealed a common focus of activation in the right IPS, with coordinates very close to the focus found here (peak activation: 40 -42 48; Euclidian distance between the present IPS peak and IPS activation found in that study: 6 mm). Together, these results suggest that common activated voxels in the right IPS in both studies might be sustained by neural populations coding for different magnitude dimensions such as numerosity, space and time. However, because of the limited spatial

resolution of fMRI and the fact that coactivation of cerebral areas does not necessarily imply a common neural code but may simply be due to the activation of distinct intermingled neural populations (Cohen Kadosh et al., 2005; Pinel et al., 2004), such evidence must be interpreted with caution. Whereas an electrophysiological study in monkeys recorded neural populations in IPS responding either to numerosity and length specifically, or to both dimensions indistinctively (Tudusciuc & Nieder, 2007), such evidence was never reported for duration and numerosity processing. In humans, direct comparisons of numerosity and duration processing at the neuroanatomical level have been very sparse but the existing evidence suggests that dissociations are possible. For instance, a recent TMS study demonstrated that stimulation of a region in the left IPS impaired performance during a numerosity comparison task while leaving a duration comparison task completely unaffected (Dormal et al., 2008). Similarly, a patient suffering from a large lesion in the right inferior parietal cortex but sparing the intraparietal sulcus, who exhibited specific deficits in temporal estimation with preserved numerical abilities, was recently reported (Cappelletti et al., 2009). Such dissociations between numerosity and time processing capacities are in favor of partially independent rather than fully-shared magnitude systems.

Chapitre 4

Dissociation of numerosity and duration processing in the left intraparietal sulcus: A transcranial magnetic stimulation study

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Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal, Andres & Pesenti (2008), publié dans *Cortex*, *44*, 462-469.

1. Abstract

A possible dissociation of duration and numerosity processing was tested in an off-line repetitive transcranial magnetic stimulation (rTMS) design. Participants had to compare the numerosity of flashed dot sequences or the duration of single dot displays before and after 15 min of 1 Hz rTMS over one of three sites (the left or right intraparietal sulcus (IPS), or the vertex chosen as a control site). Compared to the control site, performance was only slowed down for the numerosity comparison task after the left IPS stimulation, whereas it was not affected for the duration comparison task for any of the parietal sites. These results show that the parietal area critically involved in numerosity processing is not involved in duration processing, revealing at least one cerebral site where duration and numerosity comparison processes dissociate.

2. Introduction

Various animal species can discriminate numerosities (Boysen & Capaldi, 1993; Breukelaar & Dalrymple-Alford, 1998; Davis & Perusse, 1988) and durations (Roberts & Church, 1978) in experimental as well as natural conditions. These results are well accounted for by a model where the numerosity and duration of sequential events are encoded into a single accumulator through different operative modes. The impulses produced by a generator can either be summed each time an event is encountered (for numerosity processing), or at a given frequency (for duration processing) (Meck, 1997; Meck & Church, 1983; Meck et al., 1985). Such a process accords with the early preverbal numerical abilities of infants, from which adult arithmetical abilities develop (Dehaene, 1992; Dehaene et al., 1998; Gallistel & Gelman, 1992). It has therefore been assumed that the adult brain is endowed with a common functional mechanism, underlain by a common cerebral substrate, to process numerosity and duration (Walsh, 2003).

We recently investigated the interaction between duration and numerosity processing at a functional level (Dormal et al., 2006). The duration and numerosity of a series of flashing dots were simultaneously and independently manipulated in a Stroop paradigm to create congruent, incongruent and neutral trials. The participants had to compare either the total duration or the number of dots in two series. The irrelevant numerical cues conveyed by the stimuli were found to influence the temporal judgement, as demonstrated by the presence of a facilitation effect in duration processing when numerosity and duration were congruent, and an interference effect when they were incongruent. However, the temporal cues did not interfere with numerosity judgements. These results indicate that the interactions between numerosity and duration processing are limited to a unidirectional interference of numerosity on duration. Similar results were observed in adults and in 5- to 8-year-old children during a task which involved bisecting a series of dot displays flashed for 2-8 sec (Droit-Volet et al., 2003). This suggests a difference in the mandatory processing of numerosity and duration, but does not allow firm conclusions

concerning a possible common mechanism or dissociation, and hence a common or different brain substrate, to be drawn.

The assumption that numerosity and duration processes share a common cerebral substrate is thus still under debate. On the one hand, brain imaging studies are converging towards the involvement of parietal areas, and more precisely the intraparietal sulcus (IPS), in the estimation of the numerosity of sequential series of visually- or auditory-presented stimuli (Piazza et al., 2006). Bilateral activations in the IPS were found in response to visual numerosity changes when participants were passively exposed to arrays of dots in event-related adaptation paradigms (Ansari, Dhital & Siong, 2006; Cantlon et al., 2006; Piazza et al., 2004). A bilateral involvement of the posterior IPS was also demonstrated in dot enumeration or simple addition tasks (requiring explicit counting), irrespective of whether the stimuli were presented sequentially or simultaneously (Fink et al., 2001; Piazza et al., 2002; 2003; Sathian et al., 1999; Venkatraman et al., 2005). Finally, the critical role played by the left IPS in processing numerosities was demonstrated in a recent transcranial magnetic stimulation (TMS) study showing that the comparison of dot collections was slowed down after the stimulation of the left IPS (Cappelletti et al., 2007).

On the other hand, neuropsychological and brain imaging studies have suggested that duration processing involves a neural network including the frontal cortex, the cerebellum, the basal ganglia, the inferior part of the temporal lobes, the cingulate cortex, and parietal areas (Gibbon, Malapani, Dale & Gallistel, 1997; Griffiths, Johnsrude, Dean & Green, 1999; Harrington et al., 1998; Ivry & Keele, 1989; Ivry & Spencer, 2004; Jueptner et al., 1995; Matell & Meck, 2000; Nichelli et al., 1996; Tracy, Faro, Mohamed, Pinsk & Pinus, 2000). Activations of the parietal cortices, mainly in the right hemisphere, were found during time estimation and comparison (Lejeune et al., 1997; Maquet et al., 1996). A bilateral involvement of the parietal cortex was also observed during the processing of auditory and visually presented temporal rhythmic patterns

(Schubotz et al., 2000). Moreover, the temporal allocation of attention (e.g., cued allocation of attention across delays) was found to produce a left-sided activation in the IPS (Coull, Frith, Büchel & Nobre, 2000; Coull & Nobre, 1998). Finally, increased latencies were found when TMS was applied over the right posterior parietal cortex as participants were judging whether a duration interval (from 960 to 1440 msec) was longer or shorter than a standard interval (1200 msec) (Alexander et al., 2005). To sum up, although activation in areas close to the IPS has been observed in studies concerned with either numerosity or duration processes, no direct evidence for a common cerebral substrate for numerosity and duration processing has been provided so far.

Whether numerosity and duration processes do or do not share the same mechanism and neuro-anatomical substrate in the parietal cortex thus remains an open question. The aim of the present study was to determine whether the IPS area(s) known to play a crucial role in numerosity processing is(are) also involved in duration processing. In order to test the causal relationship between numerosity or duration processing and the contribution of the IPS, a TMS off-line paradigm (Robertson, Theoret & Pascual-Leone, 2003; Walsh & Pascual-Leone, 2003) was used in which participants had to compare the numerosity of flashed dot sequences or the duration of single dot displays before and after repetitive transcranial magnetic stimulation (rTMS) over the left or right IPS. To exclude unspecific effects of the duration of the TMS, the two comparison tasks were also performed before and after rTMS over the vertex, chosen as a control site. Based on the results of previous functional imaging (e.g., Piazza et al., 2006) and TMS (Cappelletti et al., 2007) studies, we predicted that IPS stimulation would slow down responses in the numerosity comparison task. The performance in the duration comparison after parietal TMS should throw light on the existence of a shared mechanism for numerosity and duration processing in this region. Under the strong assumption that numerosity and duration are encoded into a single accumulator, a similar impairment should be observed in the duration task after rTMS over the

IPS (i.e., slowing down the response latencies (RLs)). On the other hand, an absence of disruptive effects in the duration task is predicted if the IPS contribution to magnitude processing is specific to numerosity.

3. Methods

3.1 Participants

Fifteen right-handed volunteers (three females, mean ± s.d. age: 22 ± 2.7 years) gave their informed consent to participate in this experiment. All had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. In particular, all of them were negative for the risk factors associated with TMS (Keel, Smith & Wasserman, 2002). The biomedical ethical committee of the Université Catholique de Louvain approved the rTMS protocol.

3.2 Tasks and stimuli

The participants had to perform two tasks: a numerosity comparison of two successive series of flashing dots and a duration comparison of two successive single dots. Stimuli in the numerosity task were composed of a black dot (diameter: 3.5 cm) rapidly flashed at the centre of the screen. The series were constructed using non-periodic signals so that temporal ratios did not constitute a potential confounding variable, and rhythm biases and pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; Dormal et al., 2006). The total duration of the series (i.e., the duration of the dots plus the inter- dot intervals) was constant (1500 msec). In the duration task, the stimuli were composed of pairs of single black dots (diameter: 3.5 cm) presented sequentially at the centre of the screen. To avoid as far as possible potential explicit or implicit counting strategies, non-subitizable numerosities (from 5 to 9 dots, excluding 7) and short durations (from 300 to 900 msec) were used. Pairs of series/dots were chosen to constitute two distances: a large distance (3 dots for numerosity, that is, pairs 5-8 and 6-9; 200 msec for duration, that is, pairs 300-500 and 700-900) and a small distance (1 dot for numerosity, that is, pairs 5-6 and 8-9; 100 msec for duration, that is, pairs 300-400 and 800-900). The order of

presentation of the two series/dots within the pairs was also manipulated: half of the pairs began with the smaller/shorter series (S-L) and the other half with the larger/longer (L-S). The number of observations per subject in each cell of the design was 10.

3.3 Experimental procedure and rTMS protocol

Stimulus presentation and data collection were controlled by a Dell computer using a customised E-prime programme (Schneider et al., 2002) and equipped with a 17 inch screen (refresh rate: 85 Hz). The participants sat comfortably on a padded chair in a dark, quiet room, at 60 cm from the screen, and a response box (30 cm x 40 cm) with four horizontally aligned buttons lay on a cushion on their knees. At the beginning of each trial, a white rectangle (9.5 cm x 16 cm) was presented on a black background and the first series of flashing dots or a single dot was displayed in its centre for a given duration, after which the rectangle disappeared and was replaced by a black screen for 1000 msec. Then a new rectangle appeared and a second series or single dot was flashed. A black screen followed the second series/dot for a period of up to 1500 msec during which the participant could answer. As soon as the answer was given, the next trial started. In the numerosity comparison task, the participants were asked to press the furthest left button with the left index finger when the first series contained more dots than the second, and the furthest right button with the right index finger when it was the other way round; the two response buttons were 8 cm apart. In the duration comparison, participants had to decide which dot was displayed for longer, using the same key presses. The two tasks were designed to last approximately 5 min each.

rTMS was applied either over the left IPS, the right IPS, or the vertex (Cz) chosen as the control site (Figure 4.1). Each site was stimulated on a separate day and the order of stimulation of the three sites was balanced across participants. At the beginning of each session, performance on the two comparison tasks was recorded in order to obtain a baseline measure. The rTMS was then delivered at 1 Hz for 15 min using a Magstim Super-Rapid stimulator (Magstim Co. Ltd., UK)

and a 70mm figure-of-eight coil. The coil was held over the targeted area by a mechanical arm, with the handle pointing downwards and forming an angle of 45° with the sagittal midline. TMS intensity was set at 65% of maximum stimulator output. This was selected on the basis of other TMS studies that had used 1 Hz TMS to interfere with cognitive tasks (e.g., Kosslyn et al., 1999), with particular interest in the parietal cortex functions (Ashbridge, Walsh & Cowey, 1997). Immediately after the end of the TMS train, participants were asked to perform the two comparison tasks again. Task order was balanced across subjects but, for a given subject, the two tasks were always presented in the same order before and after stimulation throughout the three TMS sessions. The vertex stimulation was used as a control condition in order to reveal non-specific effects due to prolonged exposure to the tactile and auditory sensations of TMS.

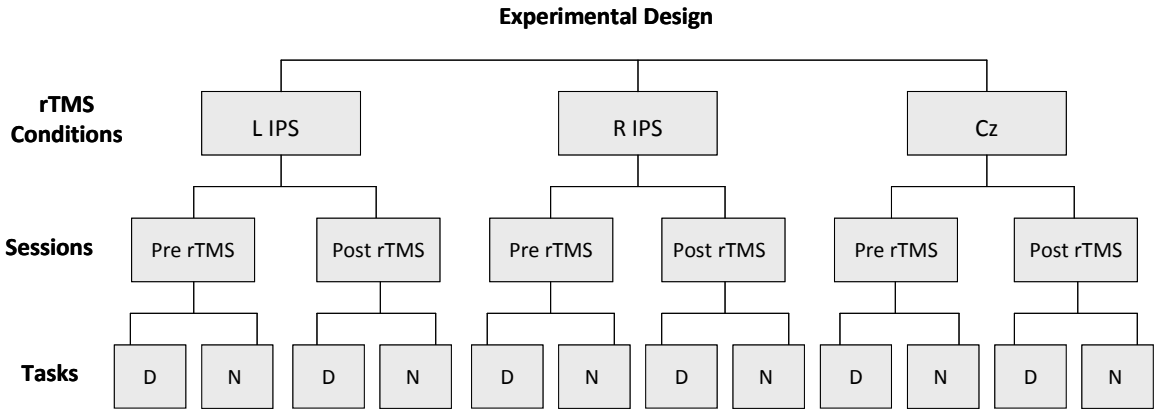

Figure 4.1: Experimental design using one possible counterbalancing order. L IPS = left intraparietal sulcus, R IPS = right intraparietal sulcus, Cz = Vertex; D= Duration task, N = Numerosity task.

The localisation of stimulation sites was carried out with a frameless stereotactic system providing on-line information about the location of the coil (Noirhomme et al., 2004). Prior to the first session, a whole brain T1-weighted magnetic-resonance image (MRI) was acquired for each participant. The co-registration between the stimulation sites and the anatomical MRIs proceeded in three steps. First, the coordinates of about 200 points distributed randomly in the physical space over the participant's scalp were obtained using a digitized pen receiver connected to a forehead reference allowing for head movements (Polhemus Isotrak II System, Kaiser Aerospace

Inc.). Second, the registration process created a transformation matrix that minimized the mean square distance between these points and a segmented scalp surface extracted from the individual MRI. Third, the figure-of-eight coil was placed over the target sites; three points were digitised at the intersection of the windings and converted within the transformation matrix; the position of the coil relative to the scalp was then indicated through the visualisation interface. A line normal to the plane of the coil was drawn from its centre to the brain, revealing the cortical impact point of TMS on both a segmented brain surface and the MRI slices.

This flexible method allowed the target sites to be visualised on individual brain images with a spatial accuracy close to a millimetre. The average location of the TMS sites in the left and right IPS was computed by normalising the individual brain images with reference to the MNI template provided by Statistical Parametric Mapping software (SPM2, Wellcome Department of Imaging Neuroscience, London, UK, <http://www.fil.ion.ac.uk/spm>; see Davare, Andres, Cosnard, Thonnard & Olivier, 2006). As shown in Figure 4.2, the parietal sites were located in the IPS (mean x, y, z ± s.d. for left IPS: -39 ± 4.6, -52 ± 8.6, 55 ± 5.5; for right IPS: 35 ± 6.2, -55 ± 7.3, 56 ± 5.9). This location is in good agreement with the results of brain imaging studies concerned with numerosity processing (e.g., Piazza et al., 2006)[9].

[9] For example, the Euclidean distance between our left and right IPS stimulation sites and the IPS areas observed in numerosity processing in Piazza et al.'s (2006) study was 15 mm and 10 mm, respectively.

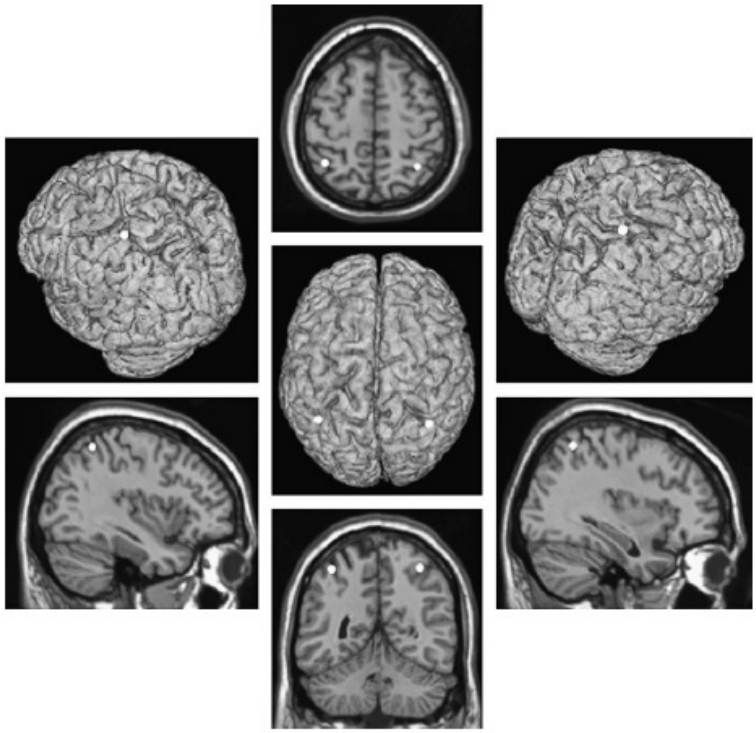

Figure 4.2: Location of the mean normalised left (-39,-52, 55) and right (35,-55, 56) IPS stimulation sites of the 15 participants on reconstructed standard brain surfaces and MRI slices. The left panels refer to the left hemisphere and the right panels to the right hemisphere. On the central panels, the axial and coronal views are oriented in the same way, following the neurological conventions.

4. Results

Trials with RLs less than 100 msec (which were considered to be anticipatory responses), or more than 1000 msec were not included in the analyses (.8% of the data).

4.1 Tasks and distance effects

To assess the equivalence of the two tasks, and to test the distance effect, an analysis of variance (ANOVA) was performed on the RLs of correct pre-TMS answers with task (numerosity, duration) and distance (large, small) as within-subject variables. There was no difference between tasks (mean ± s.d. RLs for duration: 362 ± 56 msec; numerosity: 348 ± 69 msec; $F(1,14)<1$). A significant main effect was found for distance (mean ± s.d. RLs: large distance: 342 ± 57 msec; small distance: 368 ± 66 msec; $F(1,14)=26.238$, $p<.001$): large distances were responded faster than small distances. No significant interaction was observed ($F(1,14)<1$).

The same ANOVA on error rates revealed significant main effects of task (mean ± s.d. percentage of errors: duration: 24 ± 11.5%; numerosity: 14 ± 13.2%; $F(1,14)=29.649$, $p<.001$), and distance (mean ± s.d. percentage of errors: large distance: 9 ± 8.8%; small distance: 29 ± 7.6%; $F(1,14)=248.315$, $p<.001$): more errors were produced in the duration task, and for small distances. No significant interaction was observed ($F(1,14)=1.540$, $p=.235$).

4.2 rTMS effects

To investigate the rTMS effect on the various stimulation sites, an analysis was performed on the difference between the correct RLs in post- and pre-rTMS conditions with task (numerosity, duration), stimulation site (LIPS, RIPS, Cz) and distance (large, small) as within-subject variables[10]. There was a significant main effect of task (mean RLs difference ± s.d. for duration: -42 ± 52ms, for numerosity: -21 ± 47ms; $F(1,14)=10.113$, $p<.008$): the overall decrease in the RLs observed after TMS was greater for the duration task. This effect interacted with distance ($F(1,14)=15.101$; $p<.003$): no difference between small and large distances was found for the duration task (mean RLs difference ± s.d.: large distance: -38 ± 45 ms; small distance: -46 ± 59 ms; $t(14)=-1.17$, $p>.2$), while a significant difference was observed between the two distances in the numerosity task (mean RLs difference ± s.d.: large distance: -32 ± 36 ms; small distance: -10 ± 54ms; $t(14)=3.949$, $p<.001$). Moreover, a significant 3-way interaction between task, stimulation site and distance was found ($F(2,28)=5.431$, $p<.02$).

Separate ANOVAs for duration and numerosity tasks with stimulation site and distance as within-subject variables revealed no RL difference in the duration task following stimulation over

[10] In a separate analysis, the order of tasks (duration-numerosity vs. numerosity-duration) was introduced as a supplementary between-subject variable. This was done to ensure that the interference effect of TMS applied uniformly throughout the experimental period, and to control for the presence of a possible temporal dissolution of this effect, as well as to assess a possible "priming" effect of one task over the other that could promote the use of a common neural code. Order had no main effect ($F(1,13)<1$), but it interacted with task ($F(1,13)=14.463$, $p<.002$). The RLs for the two tasks only differed significantly when duration was the second task ($t(7)=-5.128$; $p<.002$). Order did not appear in any significant interaction involving the stimulation site (all $F<1$). The same analysis on the difference between the RLs in the post- and pre-rTMS sessions relative to the control site (Cz) showed no main effect and no interaction involving order. These analyses show that the order of tasks did not affect the interference effect of TMS.

the parietal and control sites (all *p* values>.1)[11], whereas for the numerosity task, a main effect of distance was observed ($F(1,14)=15.591$; $p<.002$), as well as a significant interaction between distance and stimulation sites ($F(2,28)=3.430$; $p<.05$). *Post-hoc* paired-sample *t*-tests indicated that close numerosity discrimination was impaired after rTMS over the left IPS compared to the control site ($t(14)=2.248$, $p<.05$). No difference was observed between stimulation sites in far numerosity discrimination (left-right: $t(14)=-.597$, $p>.5$; left-Cz: $t(14)=-1.4$, $p>.1$; right-Cz: $t(14)=-.472$, $p>.6$) (Figure 4.3).

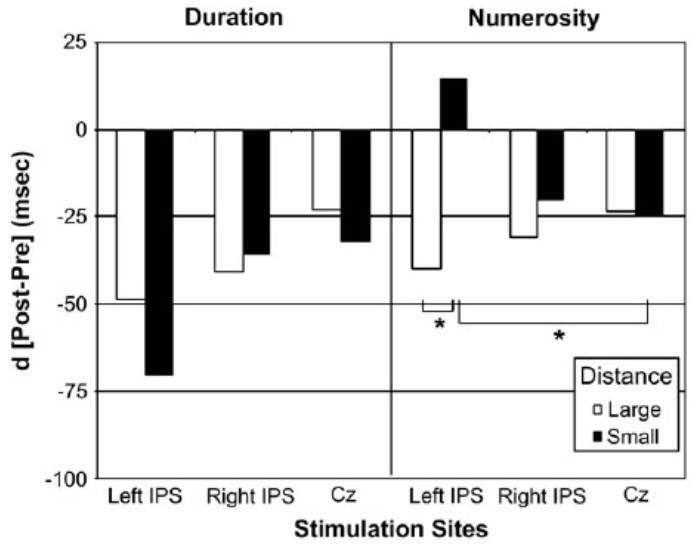

Figure 4.3: Difference in response latencies between post- and pre-rTMS session in ms for duration (left panel) and numerosity (right panel) tasks as a function of stimulation site (left IPS, right IPS or Cz) and distance (large or small). Asterisks indicate where the difference between two conditions was significant ($p<.05$).

In order to investigate this effect further, we subtracted the difference between the RLs measured post- and pre-TMS over the left and right IPS from the difference between the RLs measured post- and pre-TMS over the control site. Then, we assessed the significance of this difference using t-tests. In this analysis, a RL decrease larger after left or right IPS stimulation than after stimulation of the control site resulted in negative dRLs, whereas positive dRL values

[11] To ensure that the difference in error rates between the two tasks could not cause the absence of an interfering TMS effect in the duration task, a complementary analysis was carried out. The participants were divided into two groups according to their mean error rate (more than 20 % of errors: 10 participants, less than or equal to 20 %: 5 participants) in the duration task. An ANOVA showed no main effect (all *p* values>.2) and, most importantly, no group by site by distance interaction ($F(2,26)<1$).

indicated a greater slowing down of responses after left- or right-IPS stimulation than after the control-site stimulation. Results showed that only the dRLs computed for the left-IPS stimulation condition during the comparison of close numerosities were significantly different from 0 ($t(14)=2.317$, $p<.04$). This indicates that the left IPS stimulation impaired numerosity discrimination when the numerical distance was small (Figure 4.4). The dRLs measured in the other conditions did not differ significantly from zero[12].

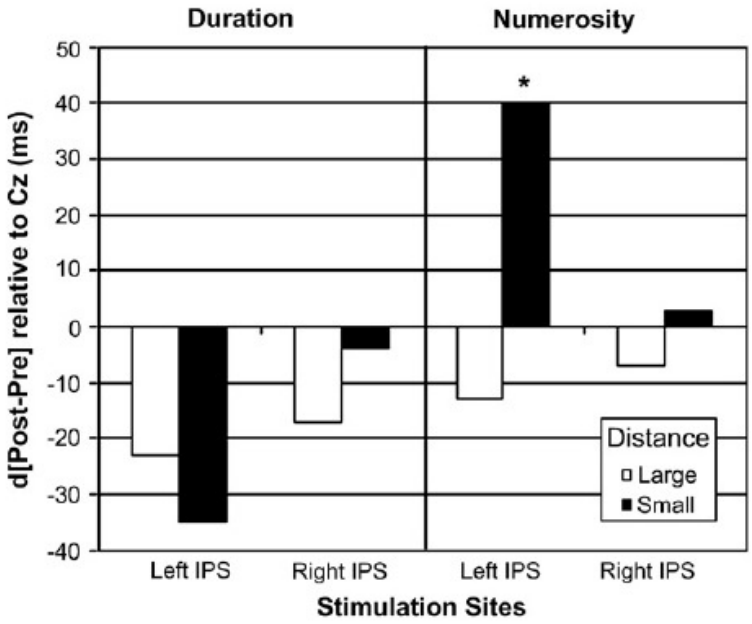

Figure 4.4: Difference in response latencies between post- and pre-rTMS session relative to the control site for duration and numerosity tasks as a function of stimulation sites and distance. Asterisks indicate which conditions were significantly different from zero ($p<.05$).

Similar analyses performed on the difference in error rates between post- and pre-rTMS conditions showed no significant main effect or interaction (all p values>.1).

[12] In their study, Cappelletti et al. (2007) observed a facilitating effect of TMS after right-IPS stimulation that was not observed here in the group analyses. At the group level, a slight facilitation tendency (7 ms) was observed after right IPS stimulation in the numerosity task; at the individual level, 7 participants showed such a facilitation tendency, but this was only statistically significantly for 2 of them. This absence of facilitation effect in our numerosity task could be due to several methodological differences with Cappelletti et al.'s study (i.e., a larger range of numerosities, simultaneous presentation, and lack of comparison to a standard task).

5. Discussion

In order to test a possible dissociation between numerosity and duration processing in the parietal cortex, we measured the performance of healthy subjects in tasks that required processing either the numerosity of flashed dot sequences or the duration of single dot displays, before and after off-line rTMS over the left or right IPS, a region known to be crucial for numerosity processing.

At the behavioural level, the results showed that in the range of selected durations and numerosities, the performance in the two comparison tasks was equally fast. Moreover, the presence of the classical distance effect (e.g., Moyer & Landauer, 1967) in both tasks showed that the participants actually performed the comparisons using the appropriate dimension. However, the two tasks were found to differ in terms of error rate. Although there was no interaction between tasks and distance, a closer look at the data clearly indicated that this difference was due to better discrimination between numerically distant sequences, approaching a ceiling effect and creating a disparity between the two tasks. The question arises whether the observed differential effects of rTMS in the numerosity and duration tasks can be explained by differences in attentional demands. Four reasons argue against this possibility. First, it is worth noting that rTMS was found to disrupt RLs but not error rates, a dissociation that has often been reported in previous studies (e.g., Alexander et al., 2005; Ashbridge et al., 1997). Second, whereas an interpretation in terms of attention allocation predicted impaired performance in the most difficult task, the disruptive effects of rTMS were observed in numerosity comparison, which was the easiest task. Third, the finding that the RL increase induced by rTMS over the left IPS was significantly larger than that induced by rTMS over the right IPS or the vertex strengthens the idea that the impairment was not due to unspecific task demands. Finally, TMS still had no effect when the analyses were performed on the subgroup of participants who had made the fewest errors in the duration task.

Our results thus support the idea that the IPS is involved in numerosity processing, as demonstrated by previous neuroimaging studies showing bilateral IPS activations (e.g., Piazza et al., 2003). Moreover, our findings specify that only the left IPS is necessary for numerosity processing, whereas the right IPS does not appear to be critically involved in this process. This interpretation is consistent with the results of a TMS study showing that left-IPS stimulation induced a RL increase when participants had to compare the numerosity of random patterns of dots (Cappelletti et al., 2007). It is also consistent with two neuropsychological studies describing patients with focal lesion of the left parietal lobe. In the first study, the patient was impaired in number comparison tasks with Arabic digits and arrays of dots (Lemer et al., 2003); in the second study, the performance of the patient in dot comparison did not differ from the performance of controls in the subitizing range but it did in the counting range (Ashkenazi et al., 2008). Moreover, we show that the numerical distance modulated the impairment induced by rTMS over the left IPS, as only the dot sequences differing by a small numerical distance were affected. This supports the idea of a left hemispheric dominance for exact quantity judgement, whereas approximate judgements of numerosity would preferentially involve the right hemisphere (Dehaene & Cohen, 1991; Piazza et al., 2006). Indeed, the more the task needs a fine and precise judgement, the more the left IPS seems to be necessary for correct performance, as demonstrated by several studies showing a correlation between the degree of involvement of the IPS and the numerical distance between the stimuli (Andres, Seron & Olivier, 2005; Cappelletti et al., 2007; Knops, Nuerk, Sparing, Foltys & Willmes, 2006; Pinel, Dehaene, Rivière & Le Bihan, 2001). The absence of deficit following rTMS over the right IPS does not mean that this region is not involved in this judgement, but indicates that it is not crucial for processing numerosities in the range selected for this study. Indeed, the activation of a right-lateralised fronto-parietal network including the intraparietal sulcus was observed when participants had to estimate larger numerosities (i.e. 15 dots) of series of visually and auditory-presented stimuli (Piazza et al., 2006).

For the duration judgement, performance after stimulation of the left or right IPS was equivalent to performance after stimulation of the control site. This result contradicts a recent TMS study in which performance in a duration comparison task was impaired after rTMS over the right posterior parietal cortex (Alexander et al., 2005). However, the stimulation sites of that study were located more posterior in the IPS (above the angular gyrus) than our sites (above the supramarginal gyrus), and these areas could be involved in other aspects of duration processing than magnitude processing, such as attention orientation. Moreover, the functional procedure used to identify the stimulation site suggests that this site also participated in a visual search. Parietal activations, mainly right lateralised, have also been reported in several neuroimaging studies (e.g., Lejeune et al., 1997), but the time course analysis of these activations suggested that the right inferior parietal cortex contributed to the early stages of duration processing (most probably reflecting encoding and maintenance operations). In contrast, the bilateral temporal, cerebellum and right dorso-lateral prefrontal activations were found to occur later on, at a time where the comparison process could take place (Rao et al., 2001). So, in these studies, the role played by parietal areas in duration could rather reflect attentional and mnesic processes not specific to the duration characteristics of the task in progress (Lewis & Miall, 2003a; Pouthas & Macar, 2005).

Although the interpretation proposed by these authors may explain the discrepancies between our results and those found in fMRI studies, it may be argued that the absence of an rTMS effect in our duration comparison task could be due to the fact that duration processing can be performed by either the left or the right IPS, so that any unilateral rTMS-induced deficit can be compensated for by the non-stimulated hemisphere. However, the great majority of brain imaging results converge to show that duration processing is lateralised in the right hemisphere (Lejeune et al., 1997; Maquet et al., 1996; Rao et al., 2001). Only one study revealed a bilateral involvement of the parietal cortex in processing rhythmic patterns (Schubotz et al., 2000), a task

in which duration may be confounded with numerosity. In other words, further brain imaging studies are necessary to identify the brain areas dedicated to processing duration magnitude. The available evidence from neuropsychological studies points to the prefrontral cortex as a possible candidate for such processing. Indeed, its lesion often leads to impaired time perception (e.g., Harrington et al., 1998). A specific relationship between the prefrontal cortex and duration processing has also been reported in an fMRI study (Rao et al., 2001). Our findings further stress the fact that the range of the selected durations is of particular importance in dissociating magnitude processing from attention allocation and memory. Finally, our experiment suggests that a double dissociation between numerosity and duration processing in the parietal and frontal cortex should be investigated, and highlights the contribution of TMS to such brain-function studies.

In conclusion, our results confirm the results of previous neuroimaging and TMS studies which reported a left IPS involvement in numerosity processing. The absence of a deficit in duration comparison following TMS over the left and right IPS indicates that this region is not crucial for duration comparisons. So, if there is a common cerebral substrate for processing these two types of magnitude (Walsh, 2003), this region is not the specific IPS area involved in numerosity processing. Future studies combining fMRI and TMS should help us to clarify this issue.

Introduction à la seconde partie expérimentale

Les trois chapitres suivants aborderont les interactions fonctionnelles et anatomiques existant entre les dimensions de numérosité et de longueur. Dans une première étude comportementale (**chapitre 5**), l'éventuelle présence d'effets de facilitation et/ou d'interférence entre les dimensions numériques et spatiales a été testée via l'utilisation d'un paradigme de type Stroop. Ensuite, dans le **chapitre 6**, afin de mettre en évidence l'éventuelle existence d'un substrat neuronal commun sous-tendant les processus d'estimation de la longueur et de la numérosité, une comparaison directe de ces deux processus grâce à la technique de l'IRMf a été réalisée. Enfin, une étude utilisant la SMT a été réalisée (**chapitre 7**), afin de compléter l'investigation des relations neuroanatomiques directes pouvant exister entre l'estimation de numérosité et de longueur et déterminer le caractère nécessaire ou non des zones communément impliquées.

Chapitre 5

Numerosity-length interference: A Stroop experiment

Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal & Pesenti (2007), publié dans *Experimental Psychology*, *54(3)*, 289-297.

1. Abstract

The existence of a common mechanism for length and numerosity processing was tested with a Stroop task. Participants compared the length or the numerosity of arrays of dots for which the two variables were manipulated independently to create congruent, incongruent or neutral pairs. Results showed that the spatial cues strongly interfered with the processing of numerosity, whereas the numerical cues only moderately interfered with the processing of length. These findings reflect a different mandatory processing of numerosity and length.

2. Introduction

Numbers and space have long been associated. Early twentieth-century philosophers discussed the functional importance of space for number comprehension, stressing both the visual and spatial properties of this relationship: numerals (i.e., conventional symbols that represent a number; Arabic numeral: *5*, verbal numeral: *five*, etc.) must be mentally visualised on a spatial medium for proper use (Bergson, 1911) and their understanding requires a knowledge of their position relative to each others (Wertheimer, 1912). Various concepts of mathematics and physics (e.g., straight line, plane, space, etc.) are grounded in this spatial-numerical interaction. In brain-damaged patients, calculation deficits and spatial disorders are frequently associated (Hartje, 1987) and temporary disturbance of the parietal cortex induced by transcranial magnetic stimulation affects judgements of size and number (Göbel et al., 2001; Bjoertomt et al., 2002). Patients with unilateral spatial neglect, who ignore their contralesional hemispace, show an ipsilesional bias not only in line bisection but also when mentally bisecting numerical intervals (e.g., giving the midpoint between 1 and 9; Zorzi et al., 2002), and take longer to compare numbers smaller than a standard than numbers which are larger (Vuilleumier, Ortigue & Brugger, 2004). Spatial neglect would thus produce representational deficits in number processing based on position. Spatial-numerical congruity effects are also reported in healthy adults. In various numerical tasks, people respond faster to small numbers with a left-hand key and large numbers with a right-hand key than vice-versa (Dehaene, Bossini, & Giraux, 1993; Fias et al., 1996; Fias et al., 2001). If, as suggested in some cognitive models, numbers are represented and processed on an analogue mental number line on which magnitudes are spatially left-to-right organised from small to large, such compatibility effects would reveal a natural mapping of this continuum onto extracorporeal physical space (Dehaene et al., 1998).

This numeral-space interaction may be partly grounded in interactions between numerosity (i.e., the number of elements in a collection) and space, as more elements usually

occupy more space. Spatial interference in numerosity judgements is frequent in children. When two arrays with the same number of elements have different lengths, children up to 7-8 years aged erroneously decide that the longer array contains more objects (Gelman, 1972; Piaget & Szeminska, 1941; Pufall & Shaw, 1972). Although they do not use length as a numerosity cue when there are less than four elements, they do not consider numerosity and length as separate dimensions when they are in conflict (Lawson, Baron & Siegel, 1974). In adults, length may still affect numerosity comparison. Indeed, with conflicting material (e.g., more elements in the shorter array), a correct answer requires the inhibition of schemes associated with perceptual salience of the rows' spatial features and leading to the wrong perceptual intuition that numerosity and length are positively correlated (the so-called visuo-spatial "length-equals-numerosity" bias; Dempster, 1995; Dixon, 1978; Houdé, 1997; Houdé & Guichart, 2001; Pascual-Leone, 1988). Numerosity and length may interact either because they are processed simultaneously through different representations leading to response competition when they diverge (Dixon, 1978), or because similar processes and/or representations are used to estimate them (Luccio & Rodani, 1983; Morris & Rule, 1988; Walsh, 2003). Recent brain-imaging studies show activations in the parietal cortex when numerical processing is involved with symbolic (e.g., Arabic or verbal numerals; Pinel et al., 1999) and non symbolic discrete material (e.g., patterns of dots: Piazza et al., 2002; 2004). The parietal cortex is known to be involved in visuo-spatial functions, including spatial attention (Gitelman et al., 1999), oculomotor planning (Corbetta et al., 1998), mental rotation (Kosslyn, DiGirolamo, Thompson & Alpert, 1998) and other coordination-transformation tasks (Zacks, Rypma, Gabrieli, Tverski & Glover, 1999). This suggests representational or processing similarities, perhaps through a numerical-spatial map built from the dorsal stream underlying spatial attention, movement perception and object tracking (Grossberg & Repin, 2003), rather than mere response competition. It has recently been proposed that duration, space and numerosity may be processed within a common system of magnitude representation (Walsh, 2003). We already recently investigated the possible interactions between

duration and numerosity processing (Dormal et al., 2006). Comparisons of the duration or numerosity of series of flashing dots were tested in a Stroop design in which the two dimensions were independently manipulated to create congruent (i.e., the series with more dots lasted longer), incongruent (i.e., the series with less dots lasted longer) and neutral pairs (i.e., numerosity was fixed and the duration varied in the comparison of duration task, whereas the duration was fixed and the number of dots varied in the numerosity comparison task). This allowed us to investigate whether and how the temporal cues interfered with numerosity processing and inversely, whether and how the numerical cues interfered with duration processing. Judging the duration of the series was found to be influenced by the irrelevant numerical information conveyed by the stimuli - it facilitated duration processing when numerosity and duration were congruent, but interfered with it when they were congruent -, whereas the temporal cues did not interfere with numerosity processing. These findings were interpreted as reflecting a probable difference in the mandatory processing of numerosity and duration.

As concerns the interaction between length and numerosity, most studies so far explored the effect of length on numerosity but not the reverse, and used stimuli for which the size of elements and their spacing were kept constant. This affects the spatial-numerical ratio leading to perceptual biases (see Appendix 5.1). The extent to which numerosity and length really interact is thus not known. Here, we used a Stroop task to assess the presence of facilitation/interference effects between numerosity and length. Participants had to compare either the numerosity or the length of two linear arrays of dots controlled for their spatial-numerical ratios. If the same mechanism underlies length and numerosity processing, then a symmetric effect of interference/facilitation should be observed: the comparison of lengths should be influenced by the number of dots and, conversely, the comparison of numerosities should be influenced by the lengths of the arrays. If the two processes are independent, no interference/facilitation effect is

expected. Finally, an asymmetric interference/facilitation effect would indicate a faster or more efficient processing of one of the dimensions than of the other.

3. Method

3.1 Participants

Thirty-six volunteers (5 left-handed, 28 females, mean age: 24 ± 2.7 years) participated; eighteen participants completed the numerosity comparison task and eighteen the length comparison task.

3.2 Tasks and stimuli

Two tasks, a numerosity and a length comparison of two linear arrays of dots, were used with three types of stimuli corresponding to the independent manipulation of numerosity and length. In *congruent pairs*, the array with more dots was the longer; in *incongruent pairs*, the array with fewer dots was the longer; in *neutral pairs*, only the relevant dimension was manipulated while the irrelevant dimension was kept constant across stimuli and could thus neither facilitate nor interfere: the numerosity was fixed (6 dots) but the length of the array varied in the length comparison, whereas the length was fixed (100 mm) but the number of dots varied in the numerosity comparison task. For the congruent and incongruent conditions, the same sets of stimuli were used in the two tasks.

The arrays were composed of black dots and used non-periodic signals so that spatial ratios were not confounded with numerosity, and density biases and pattern recognition were avoided (see Appendix 5.1). The total length of the array (i.e., diameters of the dots plus the interdot spacing) ranged from 80 to 120 mm; the numerosities ranged from 5 to 9 dots (i.e., not subitisable but below 10). The diameter of each dot (e_j) and the interdot spacing (i_j) varied from 2.5 to 15 mm for dots, from 2.5 to 20 mm for spacing; to avoid pattern recognition, each series involved at least one e_j and one i_j of 2.5 mm and one greater than 15 mm (Figure 5.1). Pairs of

arrays constituted two distances: a *large* distance (3 dots for numerosity: pair 6-9; 30 mm for length: pair 90-120 mm) and a *small* distance (1 dot for numerosity: pair 5-6; 10 mm for length: pair 80-90 mm)[13]. For each pair, five different items were constructed with the same characteristics. The order of presentation of the arrays within the pairs varied: half the pairs began with the shorter/smaller array (S-L) and the remainder with the longer/larger (L-S). To avoid comparisons based only on distance from the edge of the screen, the leftmost dot of half the pairs was presented 20 mm from the left edge and the rightmost dot of the other half 20 mm from the right edge of the screen.

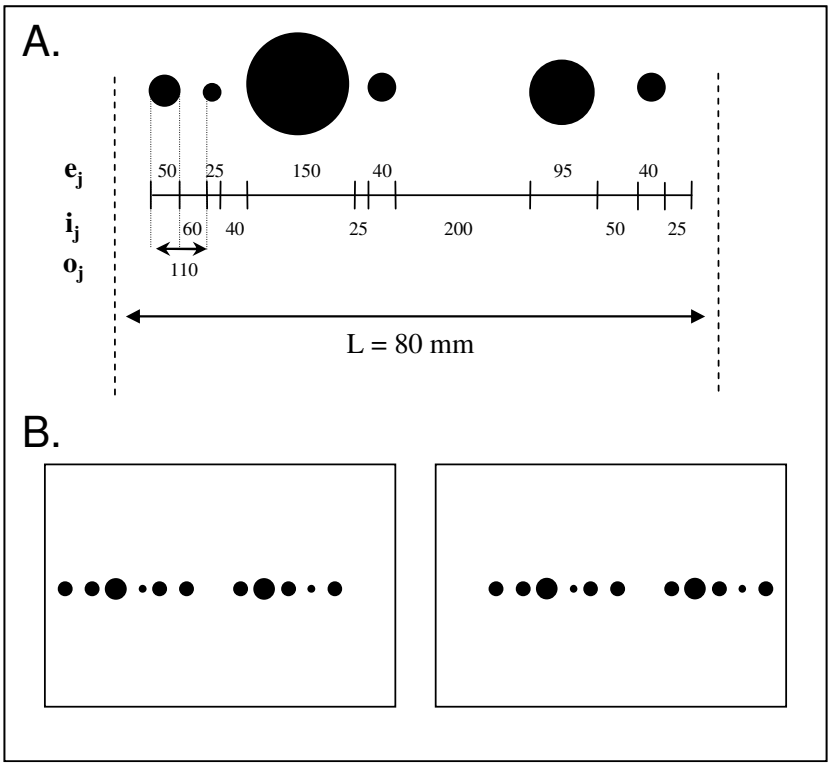

Figure 5.1: (A) Spatial attributes of the stimuli shown on a non-periodic array with 6 dots and a total length of 80 mm (l= total length; o_j= length of one dot and its adjacent spacing; e_j= dot size; i_j= interdot spacing; see Appendix 5.1 for details). (B) Example of two different stimuli composed of pairs of arrays (one shifted towards the left or one towards the right edge of the screen).

[13] These pairs were selected because they appeared to be equally fast and accurate across tasks in a pilot study carried out on the neutral conditions only, with four different pairs of stimuli by task (i.e., for numerosity small distance: 5-6, 8-9; large distance: 5-8, 6-9, for length small distance: 80-90, 110-120 mm; large distance: 80-110, 90-120 mm).

3.3 Procedure

A Macintosh computer interfaced with a 17″ screen controlled the stimuli presentation and data collection. The viewing distance was approximately 50 cm. At the beginning of each trial, two arrays were presented simultaneously for 500 ms which did not allow counting, followed by a blank screen. When the participant answered, the next trial started. Each task was composed of two blocks of 96 randomised items; a practice block of 20 items was administered first but not analysed.

Each participant was randomly assigned to one comparison task. In the numerosity comparison task, the participants had to decide which array contained more dots by pressing one of two keys on the numerical pad (key *1* with the right index finger for the left array, key *3* with the right ring finger for the right array). In the length comparison task, they had to decide which array was longer, using the same key presses. The instructions asked participants to focus on one of the dimensions and did not mention the other one.

4. Results

4.1 Interference and facilitation effects

Interference/facilitation effects were tested with an analysis of variance (ANOVA) performed on the response latencies (RLs) of correct answers with Task (numerosity *vs*. length) as a between- and Condition (congruent, incongruent *vs*. neutral pairs) as a within-subject variable. No significant difference between tasks was revealed (mean RL for numerosity: 568 ± 112 ms, length: 521 ± 75 ms; $F(1,34)=2.12$, $p=.16$). This was confirmed when only the neutral conditions from the two tasks used as baselines were directly compared: they did not differ significantly (neutral-numerosity: 544 ± 108 ms, neutral-length: 517 ± 74 ms; $t(34)<1$). A significant main effect was found for Condition (congruent: 527 ± 88 ms, incongruent: 576 ± 124 ms, neutral: 530 ± 92 ms; $F(2,33)=18.72$, $p<.001$). Post-hoc paired-sample *t*-tests indicated that the performance on incongruent pairs differed significantly from the performance on congruent ($t(35)=-3.834$, $p<.001$)

and neutral pairs (t(35)=5.112, p<.001), whereas it did not different across congruent and neutral pairs (t(35)<1). Condition and Task also interacted (F(2,33)=8.00, p<.001). Separate ANOVAs for the two tasks with Condition as a within-subject variable revealed a main effect of Condition in the numerosity task (F(2,16)=17.69, p<.001): the congruent and neutral pairs were answered faster than the incongruent ones (congruent: 540±103 ms, incongruent: 619 ± 139 ms, neutral: 544 ± 108 ms; respectively, t(17)=-4.392 and t(17)=5.972, both p<.001). This pattern of results was observed in 15 out of the 18 participants. In the length task, no significant difference was observed among conditions (congruent: 515 ± 71 ms, incongruent: 532 ± 93 ms, neutral: 517 ± 74 ms; F(2,16)=1.88, p=.18; Figure 5.2).

To ensure that the non-significant tendency for the length judgement to be slightly faster did not mask a possible (in)congruency effect of numerosity, a complementary analysis was carried out on the length task. Specific task-related processing was tested with a median split analysis performed in each within-subject cell separating the 4 fastest and the 4 slowest trials (Mac Callum, Zhang, Preacher & Rucker, 2002). An ANOVA showed a main effect of Trial Speed (mean RL for fast: 453 ± 55 ms, slow: 614 ± 107 ms; F(1,17)=109,12, p<.0001) but no Trial Speed by Condition interaction (mean RL for fast-congruent: 453 ± 55 ms, fast-incongruent: 461 ± 66 ms, fast-neutral: 443 ± 53 ms, slow-congruent: 610 ± 94 ms, slow-incongruent: 637 ± 135 ms, slow-neutral: 594 ± 114 ms; F(2,16)=2.18, p=.15). This analysis thus confirmed the absence of a significant effect of numerosity on the length judgement, whatever the speed of processing.

An ANOVA on error rates[14] revealed no differences between Tasks (mean percentage of errors for numerosity: 13.7 ± 7.1, length: 13.0 ± 4.6; F(1,34)<1), but a main effect of Condition (congruent: 8.1 ± 5.1, incongruent: 17.9 ± 11.7, neutral: 14.0 ± 8.4; F(2,33)=14.374, p<.001) and an interaction between Task and Condition (F(2,33)=5.383, p<.01): the three conditions differed in

[14] The proportions of errors in congruent conditions being low, the same ANOVA was carried out on an angular transformation of the relative error frequencies (using the *2*arcsine(sqrt(x/n))* formula). The results of this analysis being virtually similar, only the former analysis on rough frequencies is presented.

the numerosity task (congruent: 5.4 ± 2.9, incongruent: 21.9 ± 14.0, neutral: 13.7 ± 9.5; $F(2,16)=12.702$, $p<.001$) but not in the length task (congruent: 10.7 ± 5.4, incongruent: 13.8 ± 7.0, neutral: 14.4 ± 7.5; $F(2,16)=2.547$, $p=.110$). In the numerosity task, all pairs of conditions differed (congruent-incongruent: $t(17)=-4.935$, $p<0.001$; congruent-neutral: $t(17)=-3.906$, $p<.002$; incongruent-neutral: $t(17)=2.833$, $p<.02$; Figure 5.2). This pattern of results was observed in 12 out of the 18 participants.

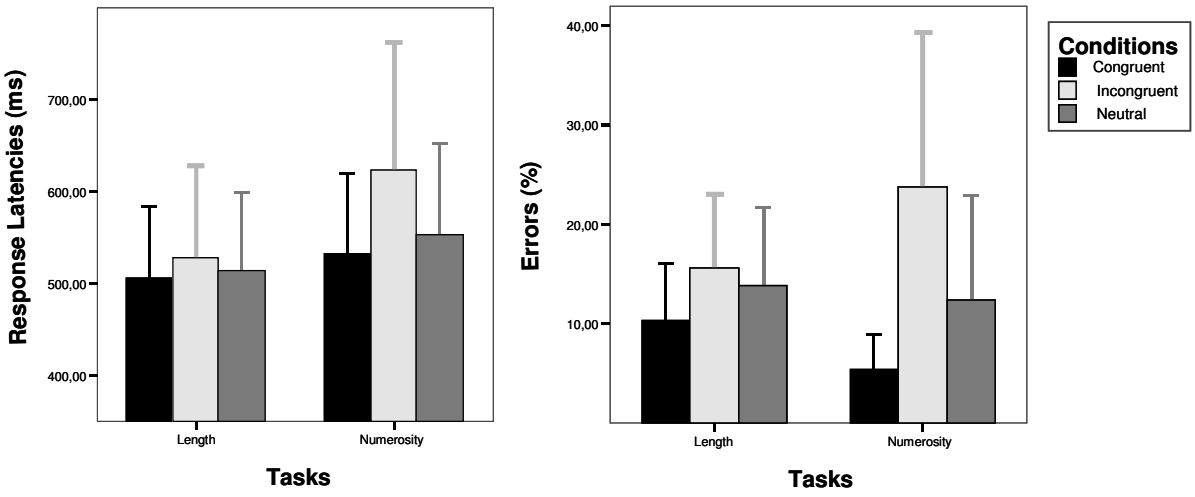

Figure 5.2: Mean percentage of errors and response latency in ms for length and numerosity tasks as a function of condition (congruent, incongruent and neutral). Errors bars indicate the standard errors of the mean.

4.2 Relevant and irrelevant distance effects

Distance effects were tested by restricting analyses to the congruent and incongruent conditions[15], with the *relevant distance* as that of the dimension to be explicitly processed (i.e., the numerical distance in the numerosity comparison and the length distance in the length comparison) and the *irrelevant distance* as that of the dimension not to be processed (i.e., the length distance in the numerosity comparison and the numerical distance in the length comparison).

[15] The neutral condition was not included, as it did not involve all the distance levels.

An ANOVA was performed on the RLs with Task (numerosity *vs.* length) as a between-, and Condition (congruent *vs*. incongruent), Relevant distance (large *vs*. small) and Irrelevant distance (large *vs*. small) as within-subject variables[16]. Condition had a significant main effect ($F(1,34)=17.23$, $p<.001$) and interacted with Task ($F(1,34)=7.02$, $p<.02$): responses were faster for congruent pairs than for incongruent ones in the numerosity but not in the length task (see above). A main effect was found for Relevant distance, responses being faster for large distances than for small ones (mean RL for large distances: 481 ± 91 ms, small distances: 622 ± 122 ms; $F(1,34)=133.45$, $p<.001$). Condition interacted with Relevant distance, the distance effect being slightly stronger in the incongruent condition ($F(1,34)=6.22$, $p<.02$). Condition also interacted with Irrelevant distance ($F(1,34)=42.67$, $p<.001$): responses were faster to the large distance than to the small distance in the congruent condition ($t(35)=-6.15$, $p<.001$) whereas the opposite was true in the incongruent condition ($t(35)=4.36$, $p<.001$); the small congruent and incongruent distances did not differ ($t(35)<1$). Moreover, Relevant and Irrelevant distances interacted ($F(1,34)=5.17$, $p<.03$): there was no difference between large and small irrelevant distances when the relevant distance was large, but responses to the large irrelevant distance were marginally faster than to the small one when the relevant distance was small. Finally, a significant three-way interaction between Condition, Relevant distance and Irrelevant distance was observed ($F(1,34)=6.66$, $p<.02$). In the congruent conditions, responses were faster for the large irrelevant distance than for the small one, especially when the relevant distance was small. In the incongruent conditions, responses to the large irrelevant distance were slower than responses to the small irrelevant difference, whatever relevant distance was presented (Figure 5.3). The other main effect and interactions were not significant.

[16] In a separate analysis, the order of presentation of the arrays (S-L *vs*. L-S) was introduced as a supplementary within-subject variable. Order had no main effect (RLs: $F(1,34)<1$; errors: $F(1,34)=2.44$, $p=.13$); it was involved in some interactions but, as it never affected the direction of the main effects of the other variables, it was not included in this analysis.

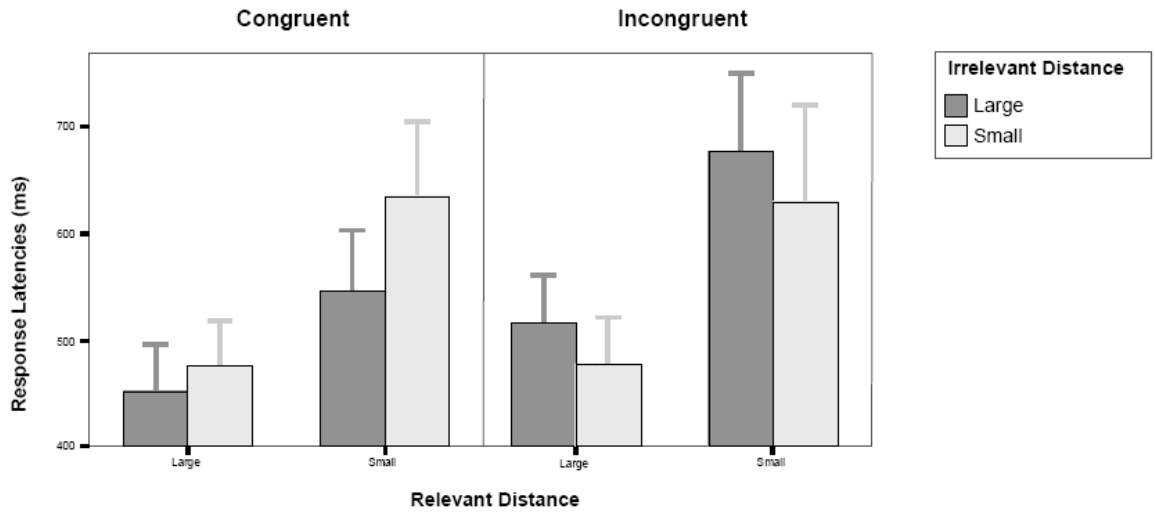

Figure 5.3: Response latency in ms for congruent and incongruent conditions as a function of the relevant and irrelevant distances (small *vs.* large). Errors bars indicate the standard errors of the mean.

For errors, the same ANOVA revealed main effects for Condition ($F(1,34)=23.51$, $p<.001$), Relevant distance (large distance: 3.5 ± 4.8, small distance: 22.5 ± 8.4; $F(1,34)= 266.23$, $p<.001$), and Irrelevant distance (large distance: 14.5 ± 6.9, small distance: 11.4 ± 6.2; $F(1,34)=10.71$, $p<0.003$). Condition and Task interacted ($F(1,34)=11.06$, $p<.003$): the congruent condition produced fewer errors than the incongruent one in the numerosity task but not in the length task (see above). There was also a significant interaction between Condition and Relevant distance ($F(1,34)=22.16$, $p<.001$) and a marginally significant three-way interaction between Condition, Relevant distance and Task ($F(1,34)=3.49$, $p<.08$): the relevant distance effect was slightly stronger in the incongruent condition, especially in the numerosity comparison task. An interaction between Condition and Irrelevant distance was observed ($F(1,34)=47.97$, $p<.001$): in the congruent condition, participants made more errors when the distance was small whereas the opposite was true in the incongruent condition. Moreover, a significant three-way interaction between Condition, Relevant distance and Irrelevant distance was found ($F(1,34)=28.16$, $p<.001$). In the congruent condition, there was a significant difference between large and small irrelevant distances when the relevant distance was small (more errors on small irrelevant distances than on

large ones), whereas no such difference was found when the relevant distance was large. In the incongruent condition, for both large and small relevant distances, participants made more errors for large than for small irrelevant distances. In these interactions the patterns were similar to those observed for latencies. Finally, a marginally significant three-way interaction between Condition, Irrelevant distance and Task was found ($F(1,34)=4.00$, $p<.06$): in both tasks, participants made more errors in the incongruent conditions than in the congruent condition, except that there was no difference on the length task when the irrelevant distance was small.

5. Discussion

5.1 Interference/facilitation and distance effects

In the numerosity comparison task, there was a clear interference effect of length on latencies (incongruent respectively 75 ms and 79 ms slower than neutral and congruent), and both facilitation and interference effects on error rates (respectively, fewer and more errors in the congruent and incongruent than in the neutral conditions). There was also an effect of the irrelevant length distance on the numerosity judgement. In the length comparison task, there was no significant difference between conditions (incongruent respectively 15 and 17 ms slower than neutral and congruent).[17] However, a large irrelevant distance facilitated judgements in the congruent conditions, especially when the relevant distance was small and thus presumably less efficient for the judgement, and interfered with it in the incongruent condition. Thus, decreasing the relevant distance increased the opportunity for the irrelevant information to influence the processing of the relevant one (Schwarz & Ischebeck, 2003). This was true in both tasks, suggesting that numerosity influenced the length judgement. Since the interaction between conditions and the irrelevant distance turned out to stem from the large irrelevant distance only, the (in)congruence effect was totally due to the large irrelevant distance. A main effect of

[17] Whereas the failure of the 15-ms difference to become significant might be a matter of statistical power, this difference was significantly smaller than that in the numerosity task.

relevant distance was observed in both tasks (the closer the numerosities, the slower and the more error-prone were the numerosity comparisons; the closer the lengths, the slower and the more error-prone were the length comparisons) showing that the participants actually performed the comparisons using the appropriate dimension (i.e., numerosity in the numerosity comparison, length in the length comparison[18]) and that the results cannot be reduced to a mere response facilitation/competition effect. Finally, the judgements on numerosity and length being equally fast and accurate in the neutral conditions considered as baselines, the observed differences are not related to differences in the attentional demands or difficulty of the relevant tasks alone. For this reason, they cannot be accounted for by differences in the relative speed of processing the two dimensions either. Such processing differences are commonly invoked to account for Stroop-like phenomena: interferences would emerge from a race in processing the relevant and irrelevant dimension when the irrelevant one is processed faster and thus "wins the race" (Dyer, 1973). Although relative speed models are well fitted to explain asymmetric interferences, the present results argue against such models (for a similar view, see Tzelgov et al., 1992). First, Horse race models attribute the existence and the magnitude of Stroop-like effects solely to the relative speed difference between the two processes. Yet, here, there was no reliable statistical difference in the latencies between the two tasks in the neutral conditions. Secondly, these models predict an interference of the fastest processed dimension on the slowest one, but not the reverse. Yet, here, although there was no global effect of numerosity, we also found a moderate effect of the numerosity cues on the length judgement through the irrelevant numerical distance effect. Thus, the slowest processed dimension (again, bearing in mind that this difference was not statistically

[18] As shown in the Appendix 5.1, length, dots perimeter, and surface were highly positively correlated and could not be disentangled in our set of stimuli. Participants may thus have strategically used one of these dimensions instead of length in their length judgements. Length, perimeter and surface being different aspects of space, our results thus hold for length taken as an instance of space processing at large. The critical point is that the moderate correlations between numerosity and these dimensions cannot account for the present pattern of results: were the participants to use surface instead of numerosity, no relevant numerical distance effect should have been observed since it was unconfounded with surface distance (see Appendix 5.1). Thus, the observed relevant numerical distance effect ensures that the participants did not use surface. Finally, perimeter and length being virtually totally confounded, the numerosity-length controls also held for numerosity-perimeter relationships.

present) interacted with the other one. Therefore, the question is: How can such an asymmetry be explained?

5.2 Mandatory processing of length and numerosity but not duration?

We investigated the relationship between numerosity and length processing with a Stroop design and tested whether processing these dimensions involved the same mechanisms. As overall performance did not differ across tasks, the asymmetrical interference effect may reflect a difference in the processing of length and numerosity: whereas length processing appears to take place automatically, numerosity processing appears not automatic enough to generate strong interference but only a weak one. This extends the results of a similar Stroop experiment where participants had to compare the duration or numerosity of series of flashing dots with congruent, incongruent and neutral pairs (Dormal et al., 2006). The numerical cues interfered with duration processing (facilitating duration processing when numerosity and duration were congruent, but interfering with it when they were incongruent), whereas duration cues did not affect numerosity processing. The observed asymmetries in interference do not allow us to draw the firm conclusions about a possible common mechanism for length, numerosity and duration processing as recently postulated (Walsh, 2003). However, taken together, these two studies do suggest at least a continuum of automaticity in processing length, numerosity and duration, from the most to the least automatic. Such a continuum of automaticity has already been proposed to account for asymmetries in Stroop-like effects without resorting onto relative speed differences in processing the relevant and irrelevant attributes (Kahneman & Chajczyk, 1983; MacLeod & Dunbar, 1988; Tzelgov et al., 1992). Automaticity may not be an all-or-none phenomenon but rather a matter of degree, and may vary continuously based on strength of processing (which may, for example, depend on practice and even be subject to attentional control; Cohen, Dunbar & McClelland, 1990). A more automatic processing interferes with a less automatic one but it is not interfered with by it. In the present context, that is in the range of selected lengths,

numerosities and durations, length would thus be the most and duration the least automatically processed dimension, leading to the specific pattern of observed asymmetries across the present numerosity-length experiment and the previous numerosity-duration one (Dormal et al., 2006). This proposal should now be tested with stimuli using all three dimensions simultaneously.

Appendix 5.1: Control of spatial and pattern ratios

In numerosity-duration discrimination tasks, the use of periodic signals (i.e., signals with constant event-interval durations) introduces two biases (Breukelaar & Dalrymple-Alford, 1998). Firstly, discrimination may rely on uncontrolled temporal attributes confounded with numerosity: when a fixed number of identical events occur periodically, temporal ratios covary with the number of events even when duration and numerosity are unconfounded by holding one constant. Secondly, when only a few sequence patterns are used, participants may respond by matching a signal to a standard stored in memory.

Similarly, in numerosity-length judgements, the total length and the number of dots correlate when periodic dots and interdot spacing are used. Indeed, when a fixed number of identical dots are presented with the same spacing, the ratios of the length of one dot and its adjacent spacing (o_j), dot size (e_j), and interdot spacing (i_j) to the total length (l) remain constant (respectively, o_j:l, e_j:l, and i_j:l; see Figure 5.1A). Pattern recognition may also help in making judgements. The solution to both problems is to use unique non-periodic signals: in every trial, the spatial pattern for each numerosity- or length-relevant signal is pseudorandomly generated by adjusting the o_j's, e_j's and i_j's. The *ratio deviation score* (DS ratio) provides a measure of deviation in the o_j:l ratio, and the *pattern deviation score* (DS pattern) provides a measure of deviation in signal patterns. Both scores can be derived from the formula

$$DS = \sqrt{\sum_{j=1}^{j=n} (D - d_j)^2} \quad . \qquad [1]$$

For the DS ratio, *D* is the total length divided by the number of dots (i.e., the length of one dot and the following spacing of the corresponding periodic signal), d_j is the actual length of each dot plus its following spacing, and *n* is the number of dots. For the DS pattern, *D* is the constant dot or interdot spacing length of the corresponding periodic signal, d_j is the current dot or interdot spacing length where *j* is odd for dots and even for interdots spacing, and *n* is the total number of dots and spacing.

For example, say a signal is composed of six dots and six interdot spacings for a total length *l* of 80 mm (see Figure 5.1A): *dot size(e)*$_1$= 5 mm, *interdot spacing(i)*$_1$= 6 mm, e_2=2.5 mm, i_2= 4 mm, e_3= 15 mm, i_3= 2.5 mm, e_4= 4 mm, i_4= 20 mm, e_5= 9.5 mm, i_5= 5 mm, e_6= 4 mm, and i_6= 2.5 mm. The ratios are derived from [1] as follows:

n: 6;

D (ratio): (80/6) = 13.3 (rounded);

D (pattern): (80/12) = 6.7 (rounded);

DS ratio:

$$= \sqrt{(13.3-(5+6))^2+(13.3-(2.5+4))^2+(13.3-(15+2.5))^2+(13.3-(4+20))^2+(13.3-(9.5+5))^2+(13.3-(4+2.5))^2}$$

= 15.2;

DS pattern:

$$= \sqrt{(6.7-5)^2+(6.7-6)^2+(6.7-2.5)^2+\ldots+(6.7-2.5)^2}$$

= 18.3.

For a periodic signal of the same total length (l= 80 mm) with six equally sized and spaced dots (e_j= 6.7 mm and i_j= 6.7 mm), both DS ratio and DS pattern would be equal to 0. Note that this is true for any other combination of e_j and i_j with ($e_j+i_j=l/n$). With nonperiodic signals, the more distant from 0 the ratios are, the lower the pattern regularity. Determining precisely the maximum DS ratio for a given series is computationally complex due to the large number of combinations of e_j and i_j values to test. In a simulation with a series of 5 dots and a length of 80 mm and with the constraints used to create the stimuli (i.e., maximum and minimum e_j and i_j, fixed final $i_{j;}$ see Method for details), the maximum DS ratio found was 28.4. This, however, occasionally produced some groupings among the dots that could have potentially led to subitizing. Therefore, the items used were qualitatively screened to exclude such series. With the selected parameters and this qualitative screening, the mean DS ratio for the five items of each category for all series varied between 14.5 and 18.7; the DS pattern was always above 17.5; moreover, the two arrays of each item had the same DS ratio. Finally, the numerosity-length correlation was 0 in the neutral condition, 0.67 in the congruent and -0.47 in the incongruent conditions.

Note that controlling the numerosity-length ratios does not result in controlling other parameters such as surface and dots perimeter. With the set of stimuli used, length and perimeter were totally positively correlated (r=1); length and surface were highly positively correlated (r=0.98, 0.95 and 0.99 for congruent, incongruent and neutral, respectively). Numerosity and surface were correlated positively for congruent (r=0.53), and negatively for incongruent (r=-0.66) and neutral (r=-0.97) stimuli. However, it is worth noting that, despite these correlations, the stimuli were equilibrated as a function of the distances of numerosity and surface: half of the small and large numerical distances were associated with small surface distances (i.e., from 0 to 79 mm^2) and the other half with large surface distances (i.e., from 82 to 230 mm^2).

Chapitre 6

Common and specific contributions of the intraparietal sulci to numerosity and length processing

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Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal & Pesenti (2009), publié dans *Human Brain Mapping*, *30*, 2466-2476.

1. Abstract

Numerical and spatial magnitude processing have long been intimately associated, leading to the suggestion that they share a common system of magnitude representation. Although separate investigations on the cerebral areas involved in numerosity and spatial estimation point towards the parietal cortex, the precise anatomical overlap, if any, has not yet been directly established. Here, functional Magnetic Resonance Imaging (fMRI) was used to localize the cerebral network involved in processing both numerosity and length. Blood oxygenation level dependent (BOLD) signal changes were measured while healthy volunteers were making numerosity comparisons on linear arrays of dots, and length comparisons on discrete linear arrays of dots and continuous rectangles. The results show the bilateral involvement of parietal regions around the intraparietal sulci (IPS) in explicit and implicit processing of numerosity, and a right lateralized occipito-parietal network activation in length processing; numerosity and length processing both activate the right IPS and the precentral gyrus. By excluding the mandatory intrinsic spatial processing of arrays, we demonstrate that the left IPS is involved in numerosity processing only, whereas the right IPS underlies a common processing mechanism or representation of spatial and numerical magnitude.

2. Introduction

It has been suggested that the parietal cortices underlie a notation- and task-independent semantic representation of numbers (Dehaene et al., 1998). The role of the parietal areas, and more precisely the intraparietal sulci (IPS), in numerical processing has been demonstrated by neuropsychological studies with brain-damaged patients (Dehaene & Cohen, 1997; Takayama et al., 1994). This finding is supported by recent brain imaging studies using number comparison (Kaufmann et al., 2005; Pesenti et al., 2000; Pinel et al., 1999; 2001), parity judgment (Thioux et al., 2005), and various arithmetic tasks (Chochon, Cohen, van de Moortele & Dehaene, 1999; Lee, 2000; Simon et al., 2002; Zago et al., 2001). Most neuroimaging and neuropsychological studies in humans have only used symbolic number tasks (i.e., tasks with Arabic or verbal numerals), but a few have investigated whether the parietal areas are also involved in processing non symbolic discrete materials (e.g., patterns of dots). This was done by using either passive habituation paradigms or tasks requiring the participants to count. Using an adaptation paradigm or variants of it, activations of the IPS of both hemispheres were indeed found in response to visual numerosity changes while participants were passively exposed to arrays of dots or squares (Ansari et al., 2006; Piazza et al., 2004). Strict selectivity is hard to establish, but the sensitivity of the IPS to numerical changes is supported by the fact that this region does not respond in the same way to other changes in the stimuli, such as shape or distribution in space (Cantlon et al., 2006). Moreover, similar neuronal adaptation and recovery effects have been observed for sets of dots and Arabic digits, supporting the idea that shared neural populations encode non symbolic and symbolic magnitudes (Piazza et al., 2007). Bilateral implication of the posterior part of the IPS has also been demonstrated in several studies using dot enumeration and simple addition tasks requiring explicit counting, irrespective of whether the stimuli were presented sequentially or simultaneously (Fink et al., 2001; Piazza et al., 2002; 2003; Sathian et al., 1999; Venkatraman et al., 2005). This may reflect the visuo-spatial processes required to orient attention to numerically

relevant dimensions of the stimuli and track their transformations. Finally, approximate non symbolic numerosity estimation has been shown to activate a right-lateralized fronto-parietal network including the IPS when subjects had to estimate the numerosity of sequential series of visually and auditory presented stimuli (Piazza et al., 2006), and the IPS foci were activated whether numerosity extended over space or over time (Castelli et al., 2006). A magnitude comparison task with non symbolic stimuli (i.e., arrays of squares) was used to compare the neural substrate of the numerical distance effect in children and adults (Ansari & Dhital, 2006). A bilateral IPS implication was observed in adult participants, with an increase in activation with age in the left hemisphere only. Areas in and around the IPS have thus been shown to be involved in symbolic and non symbolic numerical magnitude processing.

The parietal cortex is also known to be involved in visuo-spatial functions such as spatial attention (Gitelman, et al., 1999; Coull & Nobre, 1998), perception of near and far space (Marshall & Fink, 2001), and mental rotation (Kosslyn et al., 1998). Interestingly, the IPS, especially in the right hemisphere, have been found to be activated for judgments of physical size and orientation (Faillenot, Sunaert, Van Hecke, & Orban, 2001; Pinel et al., 2004), and in line bisection tasks (Fink, et al., 2000). Moreover, the left IPS has been found to be common to the comparison of Arabic numerals, lengths of lines, and amplitudes of angles (Fias et al., 2003). These findings suggest that magnitude might be represented or processed by the same mechanism for both symbolic and non symbolic continuous stimuli. Given the strong spatial dimension involved in non symbolic stimuli, space processing is a good candidate for such a common mechanism. The parietal cortex may indeed be engaged in cognitive computations on space and numbers (Walsh, 2003), which could explain why physical size, spatial location, and numbers interfere at the behavioral level (Henik & Tzelgov, 1982; Dehaene et al., 1993), and why patients with parietal damage may show deficits in both spatial and numerical bisection tasks (Zorzi et al., 2002; Rossetti et al., 2004; Vuilleumier et al., 2004). The interference of spatial cues on numerosity judgment is found in the well-known

"conservation of number" task (Piaget, 1952): when two arrays with the same number of elements have different lengths, children until the age of 7 erroneously decide that the longer array contains more objects. This reflects a misleading visuo-spatial "length-equals-number" heuristic that adults still have to inhibit to perform correctly (Daurignac, Houdé & Jouvent, 2006; Houdé, 1997; Houdé & Guichart, 2001; Leroux et al., 2006). We recently investigated the mutual influence of length and numerosity processing in a behavioral Stroop experiment in which healthy participants had to compare the length or the numerosity of arrays of dots in which the two dimensions were manipulated independently (Dormal & Pesenti, 2007). The results showed that the spatial cues interfered strongly with the numerosity judgment, whereas the numerical cues only interfered moderately with the length judgment. We interpreted these findings as reflecting a different mandatory processing of numerosity and length: with the stimuli used, length processing appears to take place automatically, whereas numerosity processing appears insufficiently automatic to generate strong interference effects. This observed asymmetry in interference did not allow us to draw firm conclusions about a possible common mechanism and hence a common brain substrate for length and numerosity processing. To test whether the numerosity-sensitive neurons in the IPS were also sensitive to line-length discrimination, recordings from single neurons in the left and right IPS of macaque monkeys were recently made while the monkeys were performing comparisons of either the number of items in multiple-dot displays or the length of lines (Tudusciuc & Nieder, 2007). The results showed that some neurons responded selectively to either the numerical magnitude or the length, whereas others responded to both dimensions. This confirmed the presence of highly distributed representations of numerical and non-numerical magnitudes, partly intermingled at the single-cell level in the monkeys' IPS.

To date, however, a direct comparison of non symbolic numerosity and length processing has not been carried out using a neuroimaging approach in humans. Whether or not numerosity

and length processing belong to the same general magnitude processing system and share the same neuroanatomical substrate in the human parietal cortex is thus still an open question. In the present study, we used fMRI to investigate and directly compare the brain's responses to numerosity and length comparison tasks. Participants had to compare the numerosity of two discrete linear arrays of dots, or the length of two discrete linear arrays of dots, or the length of two continuous black rectangles. If the same representational mechanisms and medium underlie numerosity and length processing, then the three types of comparisons should lead to similar activations, possibly in the areas around the IPS. This would provide direct support to the idea of a magnitude system underlying both (discrete) numerosity and (continuous) space processing in humans. Moreover, it is worth noting that using discrete and continuous stimuli in the length comparison tasks should allow us to isolate the brain areas specifically involved in length judgments, regardless of the type - discrete or continuous - of stimuli (by excluding those implicitly involved in the numerosity processing of discrete arrays); conversely, this should also isolate the brain areas specifically involved in numerosity processing (by including those implicitly involved in the length comparison of discrete arrays).

3. Methods

3.1 Participants

Fourteen healthy French-speaking male volunteers (mean age: 21 ± 2.3 years) participated in this study, after giving their informed written consent. All the participants were right-handed, as attested by the Edinburgh inventory questionnaire (Oldfield, 1971), had no history of neurological or psychiatric disorders, had corrected-to-normal vision, and were unaware of the purpose of the study. The experiment was non-invasive and was performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration; the experimental protocol was approved by the Biomedical Ethical Committee of the Université catholique de Louvain.

3.2 Tasks and stimuli

Three comparison tasks were used: (1) a numerosity comparison of two linear arrays of dots (denoted N, for numerosity, below), (2) a length comparison of two discrete linear arrays of dots (DL, for discrete length), and (3) a length comparison of two continuous black rectangles (CL, for continuous length).

For the first two tasks, the arrays were composed of black dots and used non-periodic signals so that spatial ratios were not confounded with numerosity, and density biases and pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; Dormal & Pesenti, 2007). The diameter of each dot (e_j) varied from 2.5 to 15 mm, while the interdot spacing (i_j) ranged from 2.5 to 20 mm; to avoid pattern recognition, each series involved at least one e_j and one i_j of 2.5 mm, one e_j of 15mm and one i_j greater than 15 mm (Figure 6.1A). Pairs of arrays were composed of 5 *vs.* 8 dots for N and were 8 cm *vs.* 9 cm long for DL. For CL, the stimuli were two black rectangles 1 cm wide and 8 *vs.* 9 cm long. The position of the arrays/rectangles within the pairs varied: for half of the pairs, the smaller/shorter array/rectangle was on the left (S-L pairs) and in the other half it was on the right (L-S pairs). A 1-cm high cross in the center of the screen separated the two elements of a pair, and the whole display occupied the center of the visual space (around 9° of visual angle). The participants were told to look at the cross throughout the task, so as to prevent possible eye saccades (Figure 6.1B). Each pair was presented for 650 ms, with a 600 ms intertrial interval between pairs (Figure 6.2A).

The three reference tasks used the same stimuli as those in the corresponding experimental tasks, except for the fact that one of the two arrays or rectangles in each pair was colored red; participants were required to indicate which array/rectangle was red. These reference tasks were equated with the experimental tasks in terms of visual complexity and manual forced-choice responses.

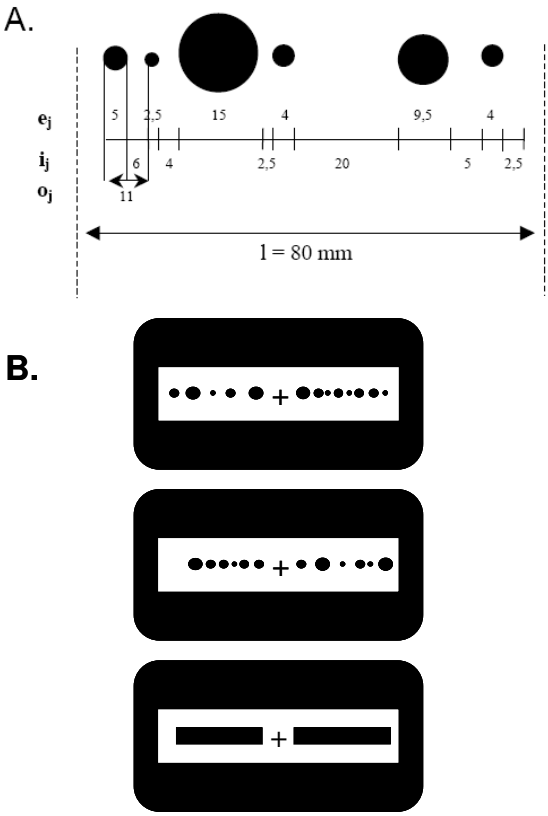

Figure 6.1: (A) Spatial attributes of the stimuli shown in a non-periodic array with 6 dots and a total length of 80 mm (l = total length; o_j = length of one dot and its adjacent spacing; e_j = dot size; i_j = interdot spacing). **(B)** Examples of stimuli composed of two linear arrays of dots for numerosity (upper panel) and discrete length comparison (middle panel), and of two continuous black rectangles for continuous length comparison (lower panel).

3.3 Experimental procedure

Back-projected images were viewed through a tilted mirror mounted on the head coil; the projector and the mirror (Silent Vision™ System, Avotec, Inc., <http://www.avotec.org>) were compatible with the MRI environment. Stimulus presentation and response recording were controlled with E-Prime (Schneider et al., 2002). Each participant undertook six acquisition runs, each consisting of eight experimental blocks of 24 sec interleaved with 12 sec fixation periods of a black cross on a white background (Figure 6.2B). In the numerosity comparison task, the participants had to decide which array contained more dots by pressing a left-hand response button on a response box for the left array and a right-hand response button for the right array. In the two length comparison tasks, they had to decide which array/rectangle was longer, using the

same button presses.

Before the fMRI experiment, each participant also undertook a preliminary training session outside the magnet room to reach a stable performance level and to check on his capacity to fixate on the central cross throughout the task. In the training session, task and procedure were the same as in the fMRI session, but there were two distances between the pairs in the arrays: a *large* distance (3 dots for numerosity: pairs 6 and 9; 3 cm for length: pairs 9 and 12 cm) and a *small* distance (1 dot for numerosity: pairs 5 and 6; 1 cm for length: pairs 8 and 9 cm)[19].

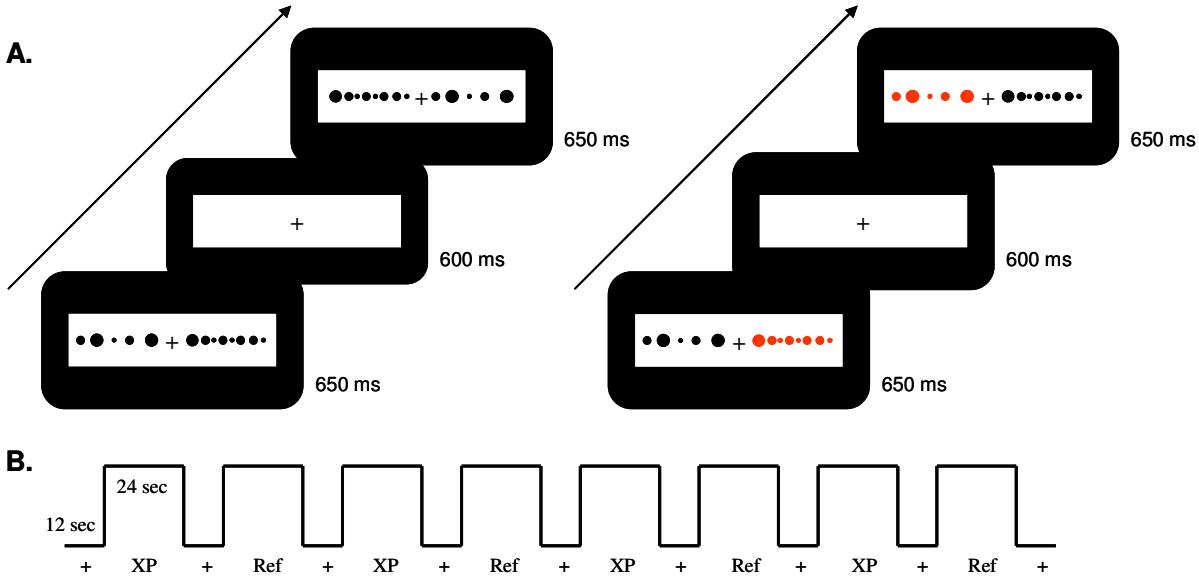

Figure 6.2: Schematic representation of the temporal structure of the experiment. (A) Examples of experimental (left) and reference (right) task: each trial was composed of a stimulus (a pair of linear arrays of dots or a pair of continuous black rectangles) displayed for 650 ms, and a fixation cross for the intertrial interval for 600 ms. For the reference task, one element of the pair was red. (B) fMRI design. Each run consisted of 8 alternations of a 12-sec fixation period (black cross on white background) and a 24-sec activation period. Each activation period corresponded to either an experimental condition or its reference condition.

[19] The results of the training session with 9 participants (for technical reasons, the training data from the first 5 participants could not be used) showed a classical distance effect (Moyer & Landauer, 1967) in the three tasks: pairs with a large distance were responded to faster and more accurately than pairs with a small distance (response latencies for large distance = 500 ± 126 ms, small = 601 ± 140ms, $F(1,8)=9.92$, $p<.02$; percentage of errors for large = 6.3 ± 10.3 %, small = 30.6 ± 17.0 %, $F(1,8)=208.18$, $p<.001$). This demonstrates that participants actually performed the comparisons using the appropriate dimensions (i.e., numerosity in the numerosity comparison, and length in the discrete and continuous comparisons).

3.4 fMRI acquisition and analysis

Functional images were acquired with a 1.5 Tesla magnetic resonance imager and a standard head coil (Gyroscan, Philips Medical Systems) as series of blood-oxygen-sensitive T2*-weighted echo-planar image volumes (GRE-EPI). Acquisition parameters were: TE = 50 ms, TR = 2000 ms, flip angle = 90°, field of view = 210 x 210 mm, slice thickness = 6 mm with no interslice gap. Each image volume comprised 20 axial slices acquired in an ascending interleaved sequence. High-resolution T1-weighted 3D fast field echo anatomical images with 110 1.5 mm contiguous axial slices were also acquired for each participant (TE = 3 ms, TR = 30 ms, flip angle= 30°, FOV= 220 x 175 mm; in-plane voxel size 0.859 x 0.859 x 1.5 mm^3). Head movement was limited by foam padding within the head coil and a restraining band across the forehead.

The data were processed and analyzed using Statistical Parametric Mapping (SPM2, Welcome Department of Cognitive Neurology, London, UK, <http://www.fil.ion.ac.uk/spm>). Functional images were (1) corrected for slice acquisition delays, (2) realigned to the first scan of the first run (closest to the anatomical scan) to correct for within- and between-run motion, (3) co-registered with the anatomical scan, (4) normalized to the MNI template using an affine fourth degree ß-spline interpolation transformation and a voxel size of 2 x 2 x 2 mm^3 after the skull and bones had been removed with a mask based on the individual anatomical images, and (5) spatially smoothed using a 10-mm FWHM Gaussian kernel.

Condition-related changes in regional brain activity were estimated for each participant by a general linear model in which the responses evoked by each condition of interest were modeled by a standard hemodynamic response function. The contrasts of interest were first computed at the individual level to identify the cerebral regions significantly activated by numerosity, discrete length, and continuous length, relative to the fixation periods used as a general baseline (respectively, *[N – fix], [DL – fix],* and *[CL – fix]*), and similarly for each reference task. Significant cerebral activations for these contrasts were then examined at the group level in

random-effect analyses using one-sample *t*-tests and analyses of variance (ANOVA), with the statistical threshold set at $p<.05$ (FWE corrected) and extending to at least 15 contiguous voxels. Given the strong *a priori* hypotheses, activations in the parietal cortices were also screened at lower, uncorrected, thresholds. The conjunction (using the Minimum Statistic compared to the Conjunction Null, MS/CN; Nichols et al., 2005) of each experimental contrast with its own reference contrast isolated the cerebral activations elicited by numerosity, discrete, and continuous length comparisons. The conjunction (MS/CN) of the two length tasks was computed in the same way to identify the cerebral activations involved in length comparison. A conjunction (MS/CN) between N and DL masked exclusively by CL revealed the cerebral activations in both explicit and implicit numerosity processing, excluding length processing. Finally, a triple conjunction analysis (MS/CN) between the three reference tasks, each contrasted to its experimental task, was carried out.

4. Results

4.1 Behavioral data

An ANOVA was performed on the response latencies (RLs) of correct answer with condition (Experimental *vs.* Reference) and task (N *vs.* DL *vs.* CL) as within-subject variables. Significant main effects were observed for condition ($F(1,13)=79.12$, $p<.001$) and task ($F(2,26)=9.63$, $p<.004$). Participants responded faster overall to the reference (334 ± 31 ms) than to the experimental (434 ± 62 ms) tasks, and were slower in numerosity and discrete length comparisons than in the continuous length comparison (N: 395 ± 41 ms, DL: 396 ± 62 ms, CL: 362 ± 37 ms; N-CL: $t(13)=5.63$, $p<.001$, DL-CL: $t(13)=3.80$, $p<.003$, and DL-N: $t(13)=0.06$, $p>.9$). Moreover, the RLs showed a condition by task interaction ($F(2,26)=6.28$, $p<.007$): the continuous length comparison was performed faster than the two other tasks, these differences being greater for experimental than for reference tasks (Figure 6.3).

A similar ANOVA on error rates revealed significant main effects of condition ($F(1,13)=34.57$, $p<.001$) and task ($F(2,26)=6.27$, $p<.03$). Participants made more errors in the experimental (10.4 ± 6.4%) than in the reference (1.1 ± 1.2%) tasks. The continuous length comparison was performed more accurately than the discrete length and numerosity comparisons (CL: 2.3 ± 2.9%, DL: 5.4 ± 2.4%, N: 9.4 ± 8.9%; CL-DL: $t(13)=4.14$, $p<.002$, CL-N: $t(13)=-3.07$, $p>.01$, and DL-N: $t(13)=-1.62$, $p>.1$). There was also a significant interaction between condition and task ($F(2,26)=5.43$, $p<.04$): error rates did not vary significantly between the three reference tasks, but in the experimental conditions, there were significantly fewer errors with the continuous length comparison than with the discrete length and numerosity comparisons (Figure 6.3).

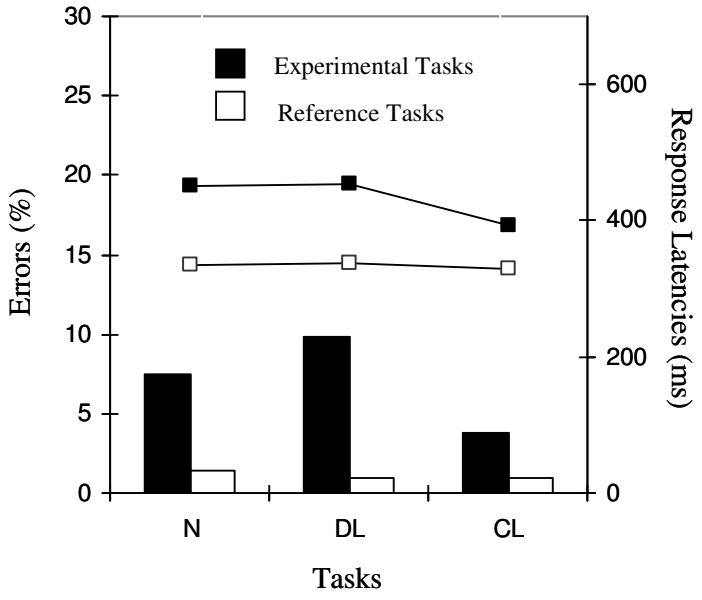

Figure 6.3: Mean percentage of errors and response latencies in milliseconds for discrete and continuous length and numerosity tasks, as a function of the task (experimental *vs.* reference).

4.2 Functional data

4.2.1 Numerosity processing

Contrasting the N task to its reference revealed the areas involved in explicit numerosity processing and comparison. Bilateral activations were found in the parietal lobes, in the depth and around the IPS, more extended in the right hemisphere. Areas of activation were also observed in the right middle and inferior frontal gyri and insula, the right supplementary motor area, the left and right occipito-temporal junction, and the left inferior frontal gyrus (Table 6.1a and Figure 6.4a). A conjunction between the N and DL tasks, each contrasted to its reference and exclusively masked by CL minus its reference, revealed the cerebral areas commonly involved in explicit (N) and implicit (DL) discrete numerosity processing, excluding length processing (Table 6.2c). These areas included the left IPS (peak at -42 -40 50), the left middle occipital gyrus and the right occipito-temporal junction. Finally, contrasted to DL and CL, the N task activated the left and right occipito-temporal and occipito-parietal junctions, and the posterior part of the right IPS.

4.2.2 Length processing

Contrasting the DL task to its reference revealed a large focus of activation in the right inferior and superior parietal lobules all around the IPS, and other large foci extending from the occipito-temporal junction to the posterior part of the superior parietal lobule, along the dorsal stream (Table 6.1b). Similar, although less extended, foci were observed in the left hemisphere. Other activation foci were found in the right frontal lobe, in the precentral gyrus and the insula, and in the SMA. In CL, only two foci were found to be activated in the right hemisphere: one in the IPS (with a local maximum at 40 -42 48) and one in the precentral gyrus (Table 6.1c). A small left superior parietal lobule activation only appeared at an uncorrected threshold (p<.003). The conjonction between DL and CL, each contrasted to its reference and exclusively masked by N minus its reference, showed no focus of activation at the corrected threshold; a tiny focus (k=5) was observed in the depth of the right inferior parietal lobule only at an uncorrected threshold

(*p*<.003) (Table 6.2a).

Table 6.1: Brain regions showing significant activation for (a) numerosity (N), (b) discrete length (DL), and (c) continuous length (CL) comparisons each compared to its own reference task (Ref).

	Brain regions	*L / R*	*k*	*x*	*y*	*z*	*t-statistic*
a	[N-Fix]-[RefN-Fix]						
	Inferior Frontal Opercule	R	473	48	6	26	10.51**
	Inferior Frontal Opercule	L	20	-48	4	26	5.35**
	Middle Frontal Gyrus	R	154	30	-2	64	6.71**
	Middle Frontal Gyrus	R	68	42	32	28	5.81**
	IPS/Inferior Parietal Lobule	R	3566	46	-38	50	9.58**
	IPS/Inferior Parietal Lobule	L	523	-32	-52	52	7.11**
	Inferior Temporal Gyrus	L	1204	-44	-74	-8	8.63**
	Supplementary Motor area	R	433	6	16	46	8.55**
	Insula	R	209	32	26	0	6.38**
b	[DL-Fix]-[RefDL-Fix]						
	IPS/Inferior Parietal Lobule	R	2808	44	-40	50	9.57**
	IPS/Inferior Parietal Lobule	L	228	-38	-46	50	6.63**
	Superior Parietal Lobule	L	29	-22	-64	52	5.47**
	Inferior Frontal Opercule	R	427	48	6	28	8.76**
	Inferior Tri Frontal Gyrus	R	40	34	28	0	5.79**
	Inferior Occipital Gyrus	L	263	-44	-76	-6	7.48**
	Middle Occipital Gyrus	L	174	-34	-84	14	6.12**
	Supplementary Motor Area	R	299	6	16	46	7.37**
	Precentral Gyrus	R	155	30	0	60	6.72**
c	[CL-Fix]-[RefCL-Fix]						
	Precentral Gyrus	R	16	50	4	26	5.56**
	IPS/Inferior Parietal Lobule	R	19	40	-42	48	5.36**
	Superior Parietal Lobule	L	26	-40	-50	64	2.82*

. = left hemisphere; R = right hemisphere; k = cluster size (number of voxels); x, y, z = stereotaxic coordinates of peak-height voxels; * = *p*-values < 0.001 uncorrected; ** = *p*-values < 0.05 FWE corrected for multiple comparisons.

4.2.3 Numerosity and length processing

A conjunction between N, DL and CL, each contrasted to its own reference, revealed the areas commonly involved in numerosity and length processing. Only the two foci observed for CL were found to be activated in all the tasks, one in the IPS and one in the precentral gyrus, both in the right hemisphere. The latter was slightly but not significantly more activated in the two tasks using discrete stimuli (i.e. N and DL; Table 6.2b and Figure 6.4b). A left IPS focus also appeared at an uncorrected threshold (*p*<.003).

4.2.4 Color processing

Finally, the conjunction between the three reference tasks, each contrasted to its own experimental task showed bilateral activation at the occipito-parietal junction and in the middle temporal gyrus (Table 6.2d), corresponding to the processing of colors.

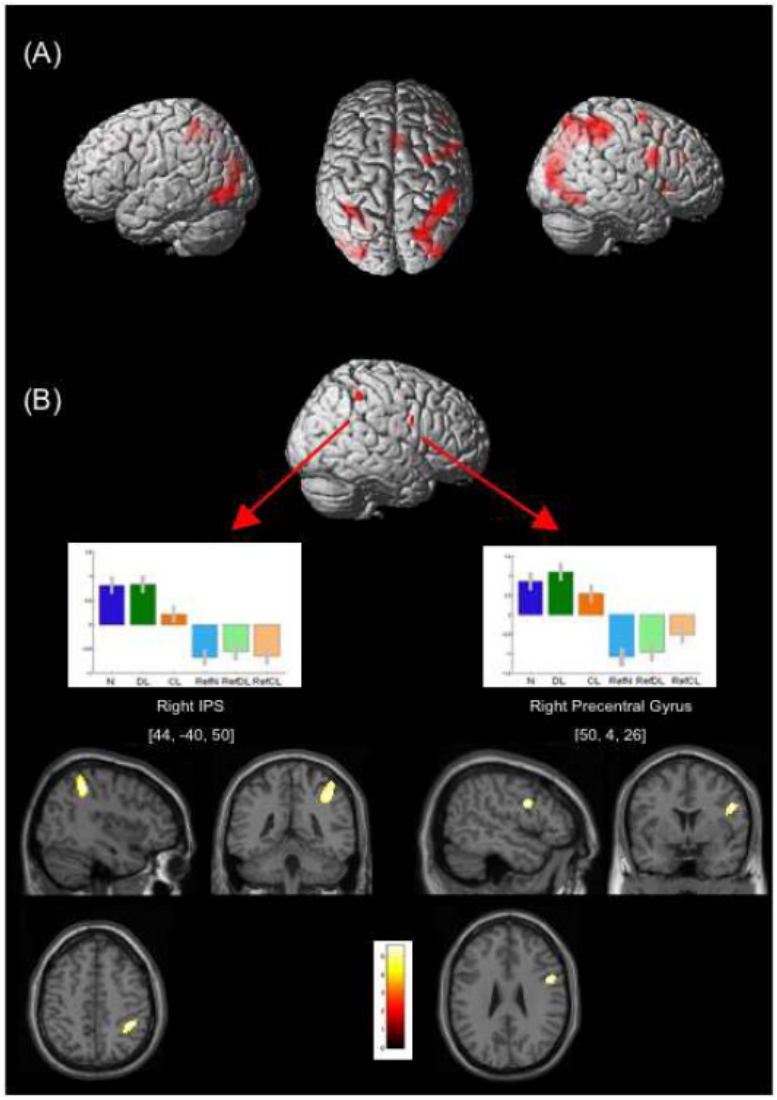

Figure 6.4: (**A**) Brain regions activated in the numerosity task (N) compared to its reference. (**B**) Brain regions activated in the conjunction of the three experimental tasks (N, DL and CL). *Upper panel:* Statistical parametric maps superimposed on a surface render of the right hemisphere. *Middle panel:* Contrast estimates for each condition in the right IPS (left) and the right precentral gyrus (right). *Lower panel:* Right IPS and precentral gyrus foci displayed on sagittal, coronal and axial slices of the MNI standard brain. (all p<.05, FWE corrected.)

5. Discussion

In our experience of daily-life, numerosity and length are intimately linked, as more objects usually occupy more space. This privileged relationship shows itself in experimental conditions through various facilitation and interference effects (Dempster, 1995; Dixon, 1978; Dormal & Pesenti, 2007; Houdé & Guichart, 2001). Recent theoretical accounts have suggested that numerosity and space may be processed and represented within a common magnitude

processing system possibly located in the parietal cortex (Walsh, 2003). Although separate investigations on the cerebral bases of numerosity and spatial processes do converge on the parietal lobes, the precise anatomical overlap, if any, between these two dimensions has not previously been directly assessed. In this study we asked participants to compare the numerosity or the length of two discrete linear arrays of dots, or the length of two continuous black rectangles in an fMRI experiment.

Table 6.2: Brain regions showing significant activation in the (a) conjunction of the two length tasks (DL and CL), (b) conjunction of the three experimental tasks (N, DL and CL), (c) conjunction of N and DL tasks masked exclusively by CL, and (d) conjunction of the three reference tasks (RefN, RefDL, and RefCL).

	Brain regions	***L / R***	***k***	***x***	***y***	***z***	***t-statistic***
a	[DL-RefDL] & [CL-RefCL] masked exclusively by [N-RefN]						
	IPS/Inferior Parietal Lobule	R	5	28	-40	44	2.90*
b	[N-RefN] & [DL-RefDL] & [CL-RefCL]						
	Precentral Gyrus	R	16	50	4	26	5.56***
	IPS/Inferior Parietal Lobule	R	19	40	-42	48	5.36***
	IPS/Superior Parietal Lobule	L	26	-40	-50	64	2.82*
c	[N-RefN] & [DL-RefDL] masked exclusively by [CL-RefCL]						
	Middle Occipital Gyrus	L	26	-30	-80	24	5.71***
	Inferior Temporal Gyrus	R	30	46	-60	-10	5.09***
	IPS/Supramarginal Gyrus	L	25	-42	-40	42	5.54***
d	[RefN-N] & [RefDL-DL] & [RefCL-CL]						
	Angular gyrus	R	20	58	-66	28	5.44***
	Precuneus	R	1012	12	-54	36	4.99**
	Middle Temporal Gyrus	L	324	-52	-62	20	4.47**
	Middle Temporal Gyrus	L	175	-58	-46	0	4.08**
	Middle Temporal Gyrus	L	16	-50	-20	18	3.70*
	Middle Temporal Gyrus	R	61	54	-14	-20	3.62**
	Medial Superior Frontal Gyrus	L	162	-12	46	34	4.11**
	Medial Superior Frontal Gyrus	L	123	-16	68	16	3.81**
	Medial Orbito-Frontal Gyrus	L	162	-4	62	-8	3.86**

L = left hemisphere; R = right hemisphere; k = cluster size (number of voxels); x, y, z = stereotaxic coordinates of peak-height voxels; * = *p*-values< 0.01 uncorrected, ** = *p*-values < 0.001 uncorrected, *** = *p*-values < 0.05 FWE corrected for multiple comparisons.

Firstly, our results show the bilateral involvement of the parietal areas in numerosity processing, as already suggested by neuropsychological and neuroimaging studies (e.g., Dehaene & Cohen, 1997; Piazza et al., 2004; 2006). They also extend this parietal involvement to the processing of discrete linear arrays of dots. More precisely, we found that the left IPS was activated by both explicit and implicit processing of numerosity, regardless of the judgment (numerosity or length) being performed on the stimuli, as demonstrated by the conjunction between numerosity and discrete length comparison. It is worth noting that length processing

was totally absent from this conjunction since the continuous length judgment had been used as an exclusive mask. This ensured that the left IPS focus was involved in the numerical aspects of numerosity processing, and not the mandatory intrinsic spatial processing. For the same reason, the IPS activation should not reflect any possible overt visual saccades, which might have been left after contrasting the experimental tasks to their references. This focus is also clearly located more anteriorly than the posterior parietal foci usually associated with the visuo-spatial processes required to orient attention to the numerically relevant dimension of the stimuli. The very short presentation time used in this experiment (i.e., 650 ms) and the requirement to fixate the central cross throughout the task to avoid eye saccades and scanning the dots make an explicit counting strategy very unlikely to have been used. However, we cannot totally exclude that the displayed numerosities implicitly triggered the verbal numerals system in the left hemsiphere, which may be the cause of the observed left-lateralized activation both in implicit and explicitly numerosity judgments. Although probably not specific to numerosity processing, it seems likely that the occipito-temporal and occipito-parietal activations left after length processing has been discarded reflect the modulation of the visuo-attentional components that is needed to individualize the dots within the arrays (Corbetta, 1998). This, with the involvement of the frontal areas sustaining attentional control, fits with previous findings on quantifying dots in the same range of numerosities (Sathian et al., 1999).

Secondly, the activations observed in continuous linear length judgment demonstrate the importance of the right parietal areas in length comparison.[20] This fits with the involvement of the right parietal cortex in many space-related processes such as the orientation of attention (Coull & Nobre, 1998), the comparison of sizes (Pinel et al., 2004), and the bisection of lines (Fink et al., 2000). Neuropsychological studies with brain-damaged patients and transcranial magnetic stimulation (TMS) experiments corroborate the dominance of the right parietal hemisphere found

[20] In a previous PET study (Fias et al., 2003), line comparison was only associated with left IPS activation. However, the authors only reported activations present in both line and symbolic number (Arabic numeral) comparisons. This may explain this left hemispheric lateralization.

for the processing of lengths. Patients with right parietal lesions, in addition to spatial neglect, had difficulty with size judgments (Milner & Harvey, 1995), length line comparison (Irving-Bell et al., 1999) and line-bisection tasks (Marshall & Halligan, 1989). Moreover contra-lateral visuo-spatial deficits were observed in healthy subjects after transient disruption of the right parietal cortex induced by focal TMS, as tested in a line-length judgment task (Fierro et al., 2000; 2001).

Finally, numerosity and length processing both rely on the activation of the right IPS and the right precentral gyrus. The right parietal area could be the site of a possible common mechanism or representation for length and numerosity processing, and be involved in both kinds of cognitive estimation. The idea that numerical and non-numerical magnitudes are represented in overlapping areas of the IPS is supported by single-cell recording studies showing that when monkeys perform comparisons of different numerosities or line lengths, some IPS neurons respond to both quantities (Tudusciuc & Nieder, 2007). Interestingly, it has been suggested that this parietal structure in monkeys may be the homologue of the horizontal segment of the IPS in humans, which is found to be activated in judgments of both physical size and numerical magnitude (Pinel et al., 2004). The fact that there is right parietal activation for both numerosity and length comparisons could at least partly explain the interferences observed in many behavioral studies between the numerical magnitude and the physical size of the stimuli in comparison tasks (Henik & Tzelgov, 1982; Pinel et al., 2004), the numerical magnitude and space location in parity judgments (Dehaene et al., 1993), the number of elements and length in numerosity comparison (Houdé, 1997; Houdé & Guichart, 2001), and numerosity and length cues in Stroop paradigms (Dormal & Pesenti, 2007). Behavioral interference effects between two physical dimensions have been shown to be stronger when they rely on the same neuronal structures (Fias et al., 2001). The shared right parietal activation could explain why the spatial cues interfered strongly with the processing of numerosity in our Stroop paradigm (Dormal & Pesenti, 2007), whereas numerical cues, processed less automatically than length and sustained

by bilateral parietal areas, only generated weak interference with length processing. Without the specific time-courses of these uni- and bilateral activations, it is hard to comment further on the mandatory processing of numerosity and/or length. A recent fMRI study compared the processing of discrete numerosities and continuous quantities, represented by displays of hues with colors changing either abruptly or smoothly in space and time (Castelli et al., 2006). Discrete numerosity comparison was found to activate the IPS more than continuous quantity comparison. This was interpreted by the authors as indicating two distinct processes. However, this conclusion goes beyond the reported data: the fact that the IPS were activated more by discrete numerosities than by continuous ones does not, of course, mean that they were not activated at all by continuous quantities. Unfortunately, the activations related to continuous quantities alone were not reported by the authors, and, so the possibility that the IPS was also activated, perhaps to a lesser extent, cannot be excluded. Our experiment clearly shows that the right IPS is activated by length processing, in the very areas which underlie the processing of numerosity.

Although the RLs and accuracy of the three comparison tasks had been equated in a pilot study[21], the numerosity comparison task turned out to be more difficult than the two length tasks, and the continuous length comparison was processed faster than the other two tasks during the fMRI session. Moreover, the experimental tasks turned out to be more time-consuming and more error prone overall than their reference tasks. As IPS activation shows some modulation as a function of increased task difficulty (Göbel, Johansen-Berg, Behrens & Rushworth, 2004), it can be argued that task complexity made some contribution to the pattern of activation we observed. However, the fact that very similar IPS activations were observed in the absence of an explicit task during passive numerosity changes (Ansari et al., 2006) suggests that response-selection requirements and task difficulty (Göbel et al., 2004) cannot be the only sources of IPS activation.

[21] ANOVAs were performed on the RLs of correct answers and on the error rates during the training session (n = 9), with task (N, DL or CL) as the within-subject variable, considering only the distance used in the fMRI experiment. These showed no significant differences between the experimental tasks (RLs for N: 542 ± 93 ms, DL: 615 ± 188 ms, CL: 584 ± 170 ms; $F(2,16)=1.76$, $p>.2$; errors for N: 15.1 ± 12.8 %, DL: 27.6 ± 9.9 %, CL = 25.1 ± 12.8, $F(2,16)=3.22$, $p>.06$). Note that the training session involved more trials than the fMRI session.

This, in turn, makes the possibility that task complexity contributed to the pattern of results we observed less plausible. To avoid this problem, future studies should try to ensure a better match in individual performance across tasks, by conducting extensive individual training prior to the experiment.

The idea that various types of magnitudes could be processed and/or represented through the same mechanisms and cerebral structures has recently been explored for physical and numerical magnitudes in grasping-related tasks (Andres, Davare, Pesenti, Olivier & Seron, 2004; Andres, Ostry, Nicol & Paus, 2008; Badets, Andres, Di Luca & Pesenti, 2007); for time, numerosity and/or physical size in comparison tasks (Oliveri et al., 2008; Dormal et al., 2008; Xuan et al., 2007); and for semantic and physical quantities (Cohen Kadosh & Henik, 2006). The present results add new evidence to this debate, but is worth noting that the spatial resolution of fMRI is still severely limited in comparison with the invasive electrophysiological techniques used with monkeys. Thus, it is possible that the right IPS activation found here in both discrete (i.e., number of dots) and continuous (i.e., length of lines) magnitude processing might be due to neurons that code specifically for one dimension. Future studies using multi-voxel pattern analyses might help to clarify the overlap between representations of numerical and non-numerical magnitude in the IPS (Ansari, 2008). TMS would be another ideal complementary technique for formulating inferences about the causal relationship between the activity of these regions and the cognitive processes under investigation. By inducing a transient virtual lesion in healthy subjects while performing numerosity or length comparison tasks, the necessary and critical contribution of these parietal areas could be directly tested.

Chapitre 7

Contribution of the right intraparietal sulcus to numerosity and length processing: An fMRI-guided TMS study

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Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal, Andres & Pesenti (soumis).

1. Abstract

The critical involvement of the left and right intraparietal sulci (IPS) in numerosity and length processing was tested through neuro-navigated repetitive transcranial magnetic stimulation (rTMS). Participants had to categorize linear arrays of dots as containing "few" or "many" dots, and filled rectangles as "short" or "long". The stimulation sites were determined for each individual participant by identifying the IPS areas showing peak activity during a number comparison task in an earlier functional magnetic resonance imaging (fMRI) study. Compared to the stimulation of the vertex (chosen as a control site), rTMS over the right IPS increased the error rate in both categorization tasks. These results indicate that the integrity of the right IPS is a necessary condition not only for discriminating numerosities but also for performing accurate judgements of lengths. We propose that these two tasks rely on a common representation and/or processing mechanism in the right IPS.

2. Introduction

Numerosity and spatial magnitude are often linked in the descriptions people give of their mental representation of numbers (Galton, 1880; Seron, Pesenti, Noel, Deloche & Cornet, 1992) and in the representations left by primitive cultures (Ifrah, 2000). Moreover, one well-known method of teaching arithmetic operations (Cuisenaire rods) relies on the manipulation of sticks of different lengths. This intimate relationship between numerosity and length has also generated a long tradition of research in cognitive neuroscience. Several behavioural studies have shown a functional interaction throughout the presence of facilitation and interference effects between numerosity and length processing. In numerosity comparison tasks, it has been shown that long arrays of elements are numerically overestimated by children (Pufall & Shaw, 1972) and even by adults (Dormal & Pesenti, 2007), and that non symbolic numerical cues can interfere with performance in length bisection (de Hevia & Spelke, 2009) and length comparison (Dormal & Pesenti, 2007) tasks.

The neural substrate of numerosity and spatial estimation has long been investigated in separate experiments, but recently neuronal recordings in monkeys and neuroimaging studies in humans have contributed to showing the existence of a specific cerebral network shared by both magnitudes. For example, the activity of single neurons in the intraparietal sulci (IPS) and prefrontal cortex was recorded in monkeys while they performed comparisons of either the number of dots in visual displays or the length of filled rectangles (Tudusciuc & Nieder, 2007; 2009). In both areas, the results showed that anatomically intermingled neurons responded selectively to either the numerosity or the length of the stimuli, or to both types of magnitudes. These findings support the idea that representations of discrete numerosities and continuous quantities share a frontoparietal network. In humans, the left IPS has been found to be activated during comparison of Arabic numerals, lengths of line and amplitudes of angles (Fias et al., 2003). Using comparison tasks with non symbolic materials (i.e., linear arrays of dots and horizontal

rectangles), we recently explored the common cerebral substrate supporting both numerosity and length estimation using functional magnetic resonance imaging (fMRI) (Dormal & Pesenti, 2009). Whereas bilateral IPS activations were found in numerosity comparisons, only the right IPS was activated in both tasks, suggesting that this area underlies a common mechanism or representation for numerosity and length processing.

Although functional imaging techniques can reveal the changes in cerebral activation correlated to a cognitive task, they do not demonstrate causal links between task performance and the activated region. To assess the causal role of the IPS in numerosity and length processing, we decided to use transcranial magnetic stimulation (TMS) coupled with an fMRI neuro-navigation method. For each participant, the TMS coil was placed over the left or right IPS to target the sites showing the greatest increase in activity during a numerosity comparison task performed in an earlier fMRI experiment. In the numerosity task, participants had to categorize linear arrays of dots as containing "few" or "many" dots; in the length task, they had to categorize filled rectangles as "short" or "long". The present study aimed to determine (1) the critical involvement of these bilateral IPS areas in numerosity processing and (2) whether these IPS areas are also causally involved in length processing.

3. Methods

3.1 Participants

Ten young healthy male adults[22] (mean age: 24 ± 0.5) took part in this experiment after giving their informed consent. All the participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), had no history of neurological or psychiatric disorder, had normal or corrected-to-normal vision, and were unaware of the purpose of the study. In addition,

[22] All the volunteers had participated in one of our previous fMRI experiments (as described in either Dormal & Pesenti, 2009 (n=6), or Dormal, Andres, Dormal & Pesenti, submitted (n=4)) and the TMS experiment took place within 24 months of the acquisition of the fMRI data.

all of them were negative for the risk factors associated with TMS (Keel et al., 2002). All the procedures were non-invasive and were performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration; the experimental protocol was approved by the Biomedical Ethical Committee of the Université Catholique de Louvain.

3.2 Tasks and stimuli

Two categorization tasks were used: (1) a numerosity categorization of linear arrays of dots (hereafter N, for numerosity) and (2) a length categorization of continuous filled rectangles (hereafter L, for length). In the N task, the participants had to decide if the arrays contained "few" (i.e., 5 or 6) or "many" (i.e., 8 or 9) dots by pressing the furthest left button on a response box with the left index finger, or the furthest right button with the right index finger. In the L task, they had to decide if the rectangles were "short" (i.e., 7.5 or 8 cm) or "long" (i.e., 9 or 9.5 cm) using the same two-choice button-press to indicate their decision.

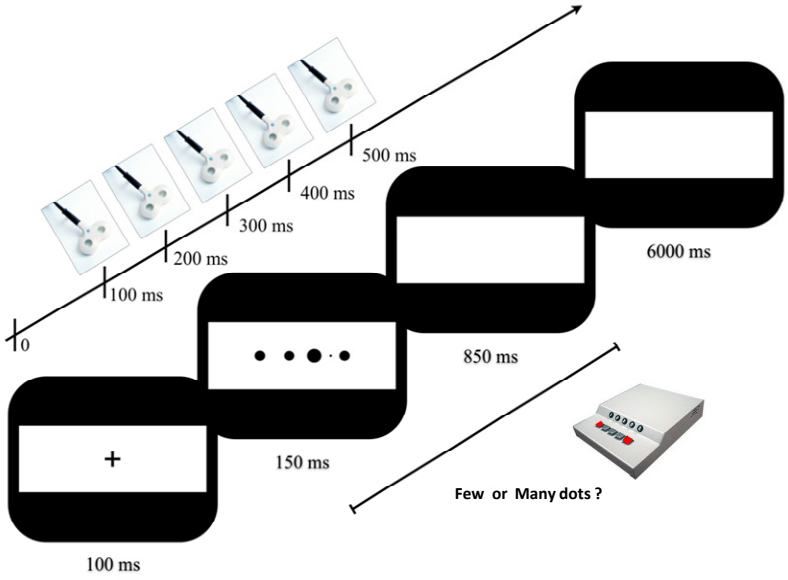

Figure 7.1: Schematic representation of the temporal structure of the numerosity categorization task. Each trial was composed of a fixation cross displayed for 100 ms, following by a stimulus (i.e., a linear array of dots) displayed for 150 ms. The participants had to decide whether the array contained "few" (left-button response) or "many" (right-button response) dots. They had 850 ms to respond and the total intertrial interval was 6850 ms. In each trial, rTMS was applied at 10Hz for 500 ms (i.e., 5 pulses) over the left or right IPS or the vertex (as a control stimulation site). The experimental design was the same for the length categorization task, except that the dot arrays were replaced by filled rectangles which the participants had to categorize as "short" or "long".

To avoid as far as possible the use of explicit or implicit counting strategies, only non-subitizable numerosities were presented in the N task, with a very short exposure time. The stimuli were composed of linear arrays of 5, 6, 8 or 9 black dots presented for 150 ms in the centre of a white rectangle (9.5 x 16 cm) on a black background (Figure 7.1). Non-periodic signals were used so that spatial ratios were not confounded with numerosity, the size of dots did not constitute a numerical cue, and pattern recognition was avoided (for more methodological details, see Dormal and Pesenti, 2007). The total length of the arrays was held constant (at 10 cm), while the diameter of each dot (e*j*) and the interdot spacing (i*j*) varied from 0.33 to 1.5 cm. In the L task, the stimuli were black rectangles 1 cm wide and 7.5, 8, 9 or 9.5 cm long, presented for 150 ms in the centre of a white rectangle (9.5 x 16 cm) on a black background. Stimuli were chosen to constitute two distances: stimuli containing 6 and 8 dots or measuring 8 or 9 cm corresponded to the small distance category, whereas those containing 5 and 9 dots or measuring 7.5 and 9.5 cm corresponded to the large distance category, for N and L task respectively.

3.3 Experimental procedure

Stimulus presentation and response recording were controlled using the e-Prime software (Schneider et al., 2002). The participants sat comfortably on a padded chair in a quiet, dark room, 60 cm from the screen, and a response box (30 cm x 40 cm) with four horizontally aligned buttons lay on a cushion on their knees. At the beginning of each trial, a white rectangle was presented on a black background and a linear array of dots or a black rectangle was displayed at its centre for 150 ms. Then, the rectangle disappeared and was replaced by a black screen for a period of 850 ms during which the participants could their answer. The intertrial interval was 6000 ms to preclude TMS carry-over effects across trials (Figure 7.1).

Based on the individual fMRI results obtained from a previous numerosity task involving either comparison or the categorization of linear arrays of dots, we defined two parietal sites for each individual. These were located along the IPS of each hemisphere using the coordinates of the

voxels showing the greatest increase of activity during the numerosity task, compared to periods of fixation (mean MNI coordinates: left IPS = -37 (±14), -51 (±14), 54 (±8); right IPS = 35 (±8), -54 (±9), 53 (±5); Figure 7.2A and Table 7.1 for precise individual coordinates)[23]. The vertex (Cz) was used as a control site.

Table 7.1: Normalized MNI coordinates (x, y, z) for the TMS sites selected as a function of the fMRI activations revealed at the individual level by the subtraction of the activations during the fixation period from those obtained during the numerosity task (at a corrected threshold of p<.05). Individual coordinates of the peak are provided for the bilateral intraparietal sulcus (IPS). *Study A: Dormal & Pesenti (2009); Study B: Dormal et al. (submitted).

Subject	**Study***	**LIPS**			**RIPS**		
		x	***y***	***z***	***x***	***y***	***z***
1	A	-20	-66	44	24	-66	42
2	A	-22	-68	60	48	-42	54
3	A	-52	-36	50	42	-42	54
4	A	-32	-50	56	32	-58	60
5	A	-56	-34	40	40	-48	56
6	A	-50	-38	54	26	-68	56
7	B	-28	-66	62	36	-54	54
8	B	-32	-46	52	30	-50	46
9	B	-50	-42	56	46	-58	52
10	B	-28	-62	66	30	-52	54
Mean		-37	-51	54	35	-54	53
SD		14	14	8	8	9	5

Before the TMS experiment, each participant undertook a practice session to reach a stable performance level. The localisation of the stimulation sites was then carried out with a frameless stereotactic system providing on-line information about the location of the coil (Noirhomme et al., 2004). Prior to the first session, a whole brain T1-weighted magnetic-resonance image (MRI) was acquired for each participant. The co-registration between the stimulation sites and the anatomical MRIs proceeded in three steps. First, the coordinates of about 200 points distributed randomly in the physical space over the participant's scalp were obtained using a digitized pen receiver connected to a forehead reference allowing for head movements (Polhemus Isotrak II System, Kaiser Aerospace Inc.). Second, the registration process created a transformation matrix

[23] Left and right IPS sites were defined at a corrected threshold (p<.05), except for three participants where we adjusted the threshold at an uncorrected level (p<.001) for the left IPS.

that minimized the mean square distance between these points and a segmented scalp surface extracted from the individual MRI. Third, the figure-of-eight coil was placed over the target sites; three points were digitized at the intersection of the windings and converted within the transformation matrix. The position of the coil relative to the scalp was then indicated through the visualisation interface. A line normal to the plane of the coil was drawn from its centre to the brain, revealing the cortical impact point of the TMS on both a segmented brain surface and the MRI slices.

This flexible method allowed the target sites to be visualised on individual brain images with a spatial accuracy close to a millimetre. For each area stimulated, there were 4 blocks, two for each experimental task (numerosity and length). Each block contained 24 items and, at the beginning of each block, the instructions were repeated and examples of arrays from each category ("few" or "short" compared to "many" or "long") were presented. The order of the stimulation sites and the order of the experimental tasks were counterbalanced across participants. Five TMS pulses (10Hz; 65% of the machine's output) were delivered at the stimulus onset using a Rapid Magstim 200 stimulator (Magstim Co. Ltd., UK) through a 70-mm inner diameter figure-of-eight coil.

4. Results

An analysis of variance (ANOVA) was performed on the response latencies (RLs) of correct answers with task (N *vs.* L), site (left IPS *vs*. right IPS *vs*. Cz) and distance (Small *vs.* Large) as within-subject variables. Significant main effects of task ($F(1,9)=20.001$, $p<.003$) and distance ($F(1,9)=6.215$, $p<.04$) were observed. The participants responded faster overall to the L task (463 ± 78 ms) than the N task (499 ± 76 ms), and faster for large distances (470 ± 74 ms) than for small ones (492 ± 80 ms). No significant effect of site was observed, and there were no significant interactions (all $p>.1$).

A similar ANOVA on error rates revealed a significant main effect of site ($F(2,18)=5.057$,

p<.02): the participants made more errors after TMS over the right IPS (10.3 ± 8.8%) than over the control site (7.2 ± 6.3 %) (*t*(9)=2.688, p<.03) (Figure 7.2B). There were no significant differences between the left (9.8 ± 8.0%) and the right IPS conditions (*t*(9)= -0.763, p>.4) or between the left IPS and the control conditions (*t*(9)=2.108, *p*=.064). There was also a main effect of distance (*F*(1,9)=39.680, *p*<.001), indicating that the participants made more errors when the magnitudes being compared were close (14.3 ± 10.6%) than when they were distant (3.9 ± 4.9%). There was no main effect of task (*F*(1,9) = 1.019, *p*>.3), and no significant interactions were observed.

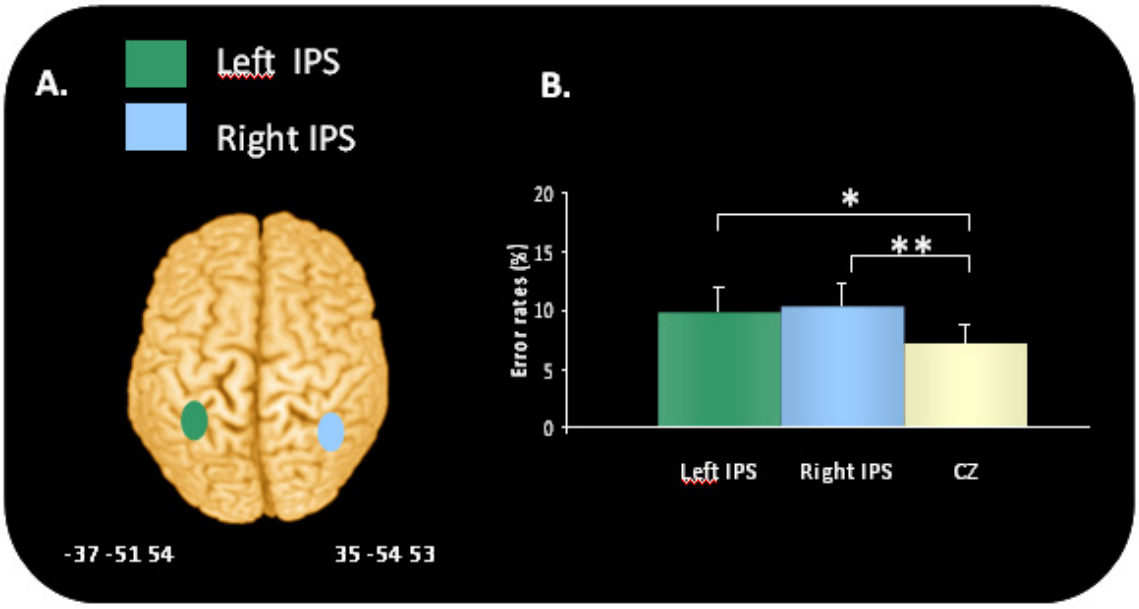

Figure 7.2: ***A***. Representation of the stimulation sites on a glass brain by ellipses centred on the average MNI coordinates of the left and right IPS stimulation points. ***B***. Mean error rate (±SE) during the two categorization tasks, while rTMS was applied over the left (green), right (blue) and control (yellow) sites. Asterisks indicate where significant increases were observed relative to the control condition (* p<.1; ** p<.05).

6. Discussion

In order to test the causal role of the left and right IPSs in numerosity and length processing, we carried out an rTMS experiment in which healthy participants had to discriminate either the numerosity of linear arrays of dots or the length of filled rectangles. Our data provide evidence that disruption of the right parietal cortex can lead to inaccurate judgements of both magnitudes. The present findings extend previous results in two ways. First, they show that the

right IPS is involved in processing both numerical and spatial dimensions, extending our previous fMRI results (Dormal & Pesenti, 2009) and supporting the idea of a common magnitude representation in the right IPS (Walsh, 2003). Second, they indicate for the first time that this parietal area is necessary for non symbolic numerosity estimation.

Interestingly, at the level of precision available with this rTMS technique, the right IPS area involved in numerosity processing was also critically implicated in the length-categorization task. This result fits with deficits observed in patients with right parietal damage, who show impairments in both spatial and numerical bisection tasks (Cappelletti et al., 2007; Marshall & Halligan, 1989; Zorzi et al., 2002), and with fMRI results showing that a distinct area within the right IPS is activated in both numerosity and length comparison tasks (Dormal & Pesenti, 2009). These findings thus suggest that numerosity and length may be processed and represented by a common magnitude-processing system located in the right parietal cortex (Bueti & Walsh, 2009; Dormal & Pesenti, 2009; Walsh, 2003).

While several fMRI studies have shown increased activity in the right IPS during non symbolic numerosity estimation (Dormal & Pesenti, 2009; Holloway, Price & Ansari, 2010; Piazza et al., 2006), the causal relationship between this region and numerosity processing remained undetected in most TMS studies so far (Cappelletti et al., 2007; Dormal et al., 2008). The only pieces of evidence of numerical deficits after right parietal lesions come from group studies where the description of the lesions was not well documented and the tasks sometimes involved additional reasoning processes (Warrington & James, 1967). The present results highlight for the first time the necessary contribution of the right IPS to numerosity processing. This original finding could be explained by the use of a distinct categorization task, which involves approximate judgements of numerosity (i.e., "few" *vs.* "more"). Indeed, several studies suggested a right hemispheric dominance for approximate judgements of numerosity, whereas exact judgements would depend on the integrity of the left hemisphere (Dehaene & Cohen, 1991; Piazza et al.,

2006). It is unclear, however, why the disruption of approximate judgements in the right IPS would not be compensated by an exact processing in the left IPS. Another plausible explanation is that the numerical processes or representations supported by each IPS are qualitatively different so that the left IPS cannot systematically take over the role of the right IPS after a lesion. Indeed, it has been proposed that each hemisphere is initially endowed with a ratio-limited magnitude processing system, available early in life and shared with other species, but that, as children start using number words or fingers to represent numerosity, a refinement is observed in the hemisphere dominant for verbal and manual abilities, that is the left hemisphere in right-handed people (Andres et al., 2005; Piazza et al., 2004; 2007). This refinement is thought to stem from the development of a more elaborate numerical system in the left IPS so that each magnitude is represented by sharper tuning curves (i.e., with less variability around the target value) than in the right IPS (Verguts & Fias, 2004). Such an account agrees with recent behavioural (Notebaert & Reynvoet, 2008), functional (Piazza et al., 2004; 2007), and TMS findings (Andres et al., 2005; Dormal et al., 2008). We therefore suggest that the developmental trajectory of numerical learning leads to a specific lateralization of numerical abilities in the adult brain: a privileged relationship is expected between exact numerosity processing in the left IPS and numerosity discrimination tasks, whereas the ratio-limited system available in the right IPS would be particularly suited to perform numerosity categorization tasks. Although further research is necessary to characterise hemispheric lateralization in numerosity processing, the present finding extends previous results to show that the representations available in the right IPS are complementary to the exact representations of the left IPS in categorization tasks. To our knowledge, this finding provides the first demonstration of a necessary contribution of the right IPS in numerosity processing.

The human IPS is a complex cerebral structure showing large inter-individual variability both anatomically (Molko et al., 2003; Zilles, Eickhoff & Palmero-Gallagher, 2003) and functionally

(Cohen Kadosh, Cohen Kadosh, Kaas, Henik & Goebel, 2007). The use of the classical stereotactic system does not take this variability into account, which might explain the absence of an impairing effect from right IPS stimulation in previous studies. The neuro-navigation method used in the present study allowed us to capture most of the inter-individual variability (Sparing, Buelte, Meister, Paus & Fink, 2008), both at the anatomical and functional levels, since the position of the TMS coil was coregistered with the brain anatomy of each participant, and the stimulation sites corresponded to the projection of the IPS sites showing the largest fMRI response when number comparison task was performed. In previous studies (Cappelletti et al., 2007; Dormal et al., 2008), some variability in the location of the stimulation sites might be expected, as they were either not functionally defined or they were projected onto a normalized representation of the individual brain.

It is worth noting that a marginal difference was found between the left IPS and the control site, suggesting a possible bilateral involvement of the IPS in numerosity and length processing. Although the involvement of the left IPS is commonly reported in numerosity comparison in TMS studies (Cappelletti et al., 2007; Dormal et al., 2008), the role of this area in length comparison is less well-established; right hemispheric dominance is generally observed in spatial processing (Sack, 2009). As no activation of the left IPS was found in a similar length comparison task (Dormal & Pesenti, 2009), extreme caution is required before concluding that this region has any specific involvement in length judgements. Recent fMRI-TMS combined studies have demonstrated the propagation of left IPS stimulation to the right hemisphere via interhemispheric connections (Bestmann, Ruff, Driver & Blankenburg, 2008; Driver, Blankenburg, Bestmann, Vanduffel & Ruff, 2009), and this may explain the presence of this left hemisphere effect in the present study. Further investigation is clearly required to resolve this issue.

Introduction à la troisième partie expérimentale

Les deux derniers chapitres de ce travail aborderont les liens fonctionnels et neuroanatomiques existant entre les dimensions de numérosité, de longueur et de durée simultanément. Tout d'abord, une étude comportementale utilisant un paradigme de type Stroop va investiguer de façon systématique les effets de facilitation et d'interférence existant entre le traitement de la numérosité, de la longueur et de la durée (**chapitre 8**). Enfin, une étude en IRMf a été réalisée (**chapitre 9**) afin de mettre en évidence les zones cérébrales impliquées spécifiquement et/ou communément dans les processus d'estimation de numérosités présentées dans le temps (i.e., présentation séquentielle) ou présentées dans l'espace (i.e., présentation simultanée).

Chapitre 8

Processing numerosity, length and duration in a 3-dimensional Stroop-like task: Towards a gradient of processing automaticity?

Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal & Pesenti (en préparation).

1. Abstract

The existence of a possible continuum of automaticity for numerosity, length and duration processing was tested with a three-dimensional Stroop-like paradigm. Participants had to compare either the numerosity, the length or the duration of two successive linear arrays of sequentially flashed dots in which the three dimensions were manipulated independently to create congruent, incongruent or neutral pairs. The results show that numerosity and length both affected duration processing separately and cumulatively, whereas temporal cues did not influence judgements of numerosity or length. Moreover, length and numerosity influenced each other, with numerical cues having a stronger influence on length processing than vice versa. These findings support the idea that numerosity, length and duration, are processed with different degrees of automaticity, with numerosity being processed most, and duration least, automatically in sequentially presented stimuli.

2. Introduction

The idea of a single representational mechanism supporting magnitude processing was first developed for time and numerosity in the Accumulator Model (Meck & Church, 1983) and later extended by the ATOM Model (A Theory of Magnitude; Bueti & Walsh, 2009; Walsh, 2003). In the last ten years it has led to a profusion of behavioural and brain imaging studies looking for possible interactions between various magnitude dimensions, including numerical, spatial and temporal magnitudes.

Firstly, a robust interference effect of the numerical dimension on duration processing was observed, using either symbolic or non-symbolic stimuli, both in children (Droit-Volet et al., 2003) and in adults (Brown, 1997; Dormal et al., 2006; Oliveri et al., 2008; Roitman et al., 2007; Xuan et al., 2007). The less-explored reverse influence of duration on numerosity processing seemed not to be so evident (only reported by Brown, 1997; see Table 8.1). For instance, although irrelevant to the task, the magnitude of Arabic digits was shown to interfere with duration judgement: when asked to estimate the duration of presentation of Arabic digits, participants underestimated the duration of small digits whereas they overestimated the duration of large digits (Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007). Moreover, the numerosity of rapidly flashed dot sequences or simultaneously presented dot arrays interacted with duration comparisons: numerical cues facilitated duration processing when numerosity and duration were congruent, and interfered with it when they were incongruent, but duration cues did not affect numerosity judgements (Dormal et al., 2006; Xuan et al., 2007). We tentatively explained this asymmetric effect of the numerical dimension on duration by different mandatory processing, the unilateral effect probably reflecting a more automatic processing of numerosity than of duration (Dormal et al., 2006).

Secondly, the interaction between space and time has been investigated through the concept of speed in many psychophysical studies over the past century, revealing the existence of

two important effects. In a classical paradigm in which three horizontally aligned visual signals were flashed successively, forming two distinct spatio-temporal intervals, participants had to compare either the spatial or the temporal extents of these intervals. The results show that duration comparison is influenced by the spatial distance between the flashed signals (the *kappa* effect; Cohen, Hansel & Sylvester, 1953) and, conversely, the temporal intervals between stimuli interfere with length comparison (the *tau* effect; Helson, 1930). More recently, the kappa effect was also observed in other experimental contexts, through the presence of compatibility between temporal estimation and the available spatial cues (Table 8.1): the duration of exposure of small squares was perceived to be shorter than the duration of exposure of large squares (Xuan et al., 2007), and the duration of stimuli presented in the left hemispace was underestimated, whereas the duration of stimuli presented in the right hemispace was overestimated (Vicario et al., 2008). Similarly, the spatial extent interfered systematically with judgements on the duration of presentation (Casasanto & Boroditsky, 2008). This last study did not replicate the classic tau effect in that it only an asymmetric interaction between spatial extent and duration was found, duration never interfering with distance processing.

Finally, the idea of an association between numbers and space is supported by various pieces of evidence (Table 8.2). It is worth noting that the term "space" encompasses a large variety of cognitive and motor processes; here, we only consider experiments investigating space conceived as length. Length interference in numerosity judgements is frequent in children who numerically overestimate the longest array of elements, demonstrating the dominant influence of length over numerosity (Houdé & Guichart, 2001; Piaget, 1952; Pufall & Shaw, 1972). Reciprocally, numerosity influences performance on visuo-spatial cognitive tasks even when the numerical information is irrelevant for the decision. Indeed, participants show systematic spatial biases towards the larger magnitude when they have to bisect a horizontal line flanked by Arabic digits (Fischer, 2001) or non-symbolic dot arrays (de Hevia & Spelke, 2009), and they under-estimate the

space between two small Arabic numbers while over-estimating the space between two large numbers (de Hevia et al., 2008).

Table 8.1: Studies investigating relations between (a) numerical and temporal dimensions and (b) temporal and spatial dimensions.

Dimensions	Studies	Links explored	Tasks	Materials	Results
(a) Numerical & Duration	1. Brown, 1997	Num⇔Dur	Dual-task paradigm : duration production and mental arithmetic tasks	N = Substraction (between 2 and 99) D = 2 or 5 sec	Mutual interference between mental arithmetic and duration production
	2. Droit-Volet et al., 2003	Num⇔Dur	Temporal and numerical bisection tasks	Sequence of dots in which time and numerosity co-vary N = between 2 and 8 D = between 2 and 8 sec	Unilateral interference of numerosity on duration task
	3. Dormal et al., 2006	Num⇔Dur	Stroop-like paradigm : duration or numerosity comparison task	Visual flashed dot series N = between 5 and 9 dots D = between 1200 and 2100 ms	Unilateral interference of numerosity on duration task
	4. Roitman et al., 2007	Num⇔Dur	Temporal and numerical bisection tasks	Visual flashed dot series N = between 4 and 16 D = between 0.8 and 3.2 sec	Numerical sensitivity > Temporal sensitivity
	5. Xuan et al., 2007	Num -> Dur	Temporal comparison task	N = Arabic digits : 1, 2, 8 or 9 Dot arrays = 1, 2, 8 or 9 dots D = between 600 and 937 ms	Interference of numerical dimension on duration task
	6. Oliveri et al., 2008	Num -> Dur	Time estimation task	N = Arabic digits : 1, 5 or 9 D = 250, 300 or 350 ms	Interference of numerical dimension on duration task
	7. Vicario et al., 2008	Num -> Dur	Duration comparison task	N = Arabic digits : 1 and 9 D = between 150 and 450 ms	Interference of numerical dimension on duration task
(b) Duration & Space	1. Casasanto & Boroditsky, 2008	Dur ⇔ Space	Length or duration reproduction tasks	D = between 1000 and 5000 ms S = between 200 and 800 pixels	Unilateral interference of spatial dimension on duration task
	2. Xuan et al., 2007	Space -> Dur	Duration comparison task	D = between 600 and 937 ms S = Open square : 0.8, 1.2, 3.0 and 3.4 d°	Interference of size on duration task
	5. Vicario et al., 2008	Space -> Dur	Duration comparison task	D = between 150 and 450 ms S = left or right spatial position	Interference of spatial dimension on duration task

Only two paradigms conceptions have been used to simultaneously explore the impact of numerosity on spatial processing and conversely, the influence of spatial cues on numerosity processing, one with symbolic Arabic digits and the other with non-symbolic numerosities. In the size–congruity paradigm, in which the numerical magnitude and the physical size of Arabic digits are varied independently, participants have to judge either the physical size of the digits while ignoring the numerical magnitudes, or the numerical magnitude while ignoring the physical size: the results show that physical size interferes with numerical processing and vice-versa, participants being unable to ignore the irrelevant dimension and implicitly processing it (e.g., Henik & Tzelgov, 1982). The mutual influence of length and numerosity processing was also recently investigated in a Stroop-like experiment in which participants had to compare the length or the numerosity of arrays of dots in which the two dimensions were manipulated

independently: whereas spatial cues strongly interfered with numerosity processing, numerical cues interfered only moderately with length judgements (Dormal & Pesenti, 2007). As in duration-numerosity Stroop experiment mentioned above (Dormal et al., 2006), these findings reflect different mandatory processing of these dimensions: length appears to be automatically processed whereas numerosity processing is not automatic enough to interfere with length processing.

Taken together, the particular pattern of asymmetric results observed in these two studies has led to the suggestions that there is a continuum of automaticity in processing length, numerosity and duration. To our knowledge, only one study has investigated these three dimensions in the same experiment by exploring the influence of numerical and spatial cues on duration perception, and found a pattern of interference which was in accord with this continuum hypothesis (Vicario et al., 2008). In that study, participants had to estimate the duration of an Arabic digit presented either in the left or in the right hemispace. As mentioned above, a disturbance effect of numerical magnitude and the side of presentation on the duration judgement was observed. Moreover, when these two irrelevant dimensions were manipulated simultaneously, a cumulative effect was observed: the duration of a small digit (i.e., 1) was underestimated more when it was presented in the left hemispace and inversely, the duration of a large digit (i.e., 9) was more overestimated when it was presented in the right hemispace.

All these studies have tried to show how the dimensions interact, but most of them only explored unidirectional interfering effects and, most of the time, only used symbolic numerical stimuli. To date, the mutual and bidirectional interactions of numerosity, length and duration have not been investigated within the same experimental design. It is thus hard to exclude the possibility that differences in materials or experimental set-up could have induced these asymmetries. In the present study, we directly tested the proposal of a gradient of automaticity in a Stroop-like task with stimuli in which the three dimensions were manipulated simultaneously.

The participants had to compare either the numerosity, the length or the total duration of two successively presented linear arrays of dots. We tested (1) whether there was any direct facilitating or interfering effect of each irrelevant dimension on the relevant dimension, and the nature of any such interference (i.e., symmetric or asymmetric effect), and (2) whether there was any joint effect of the manipulation of the two irrelevant dimensions and the nature of any such interaction (i.e., cumulative effect or interaction, facilitation or interference).

Table 8.2: Studies investigating relations between (c) numerical and spatial dimensions and (d) numerical, temporal and spatial dimensions.

Dimensions	Studies	Links explored	Tasks	Materials	Results
(c) Numerical & Space	1. Pufall & Shaw, 1972	Space -> Num	Numerosity comparison	Two rows of dots N = 5, 7 or 9 dots	Interference of length on numerosity task
	2. Henik & Tzelgov, 1982	Space ⇔ Num	Physical or numerical size comparison	N = Arabic digits : between 2 and 8	Mutual interference between spatial and numerical dimensions
	3. Fisher, 2001	Num -> Space	Line bisection task	N = Arabic digits composing the line or placing in the extremities of an horizontal line : 1, 2, 8 or 9 S = Left or right side responses	Interference of numerical dimension on bisection task
	4. de Hevia et al., 2007	Num -> Space	Length reproduction task	Extend delimited by two arabic digits : 1, 2, 8 or 9	Interference of numerical dimension on length task
	5. Dormal & Pesenti, 2007	Num ⇔ Space	Numerosity or length comparison tasks	N = Linear array of dots : 5, 6 or 9 dots S = between 80 and 120 mm	Mutual interference between numerosity and length dimensions
	6. de Hevia et al., 2008	Num -> Space	Line bisection task	Pattern of dots in the extremities of an horizontal line : 2 or 9 dots	Interference of numerical dimension on bisection task
(d) Numerical & Duration & Space	1. Vicario et al., 2008	Num & Space -> Dur	Duration comparison task	D = between 150 and 450 ms S = left or right spatial position N = arabic digits : 1 or 9	Joint interference of numerical and spatial dimensions on duration task

2. Methods

2.1 Participants

A total of 54 volunteers (4 left-handed, 37 females, mean age: 21 ± 5.02 years) took part in this experiment; 18 participants were randomly assigned to each comparison task (i.e., the numerosity, length and duration comparisons, see below). All the participants had normal or corrected-to-normal vision, and were unaware of the purpose of the study. All the procedures

were non-invasive and were performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration.

3.2 Tasks and stimuli

The experiment was composed of three distinct tasks: (1) a numerosity comparison, (2) a length comparison and (3) a duration comparison of two successive linear arrays of flashed dots. In the numerosity comparison task, the participants had to decide which array contained more dots by pressing one of two 13cm-distant keys on a keyboard (with the left index finger for the first array, with the right index finger for the second array). In the length comparison task, they had to decide which array was longer, and in the duration comparison, which array lasted longer from the appearance of the first dot to the disappearance of the array, using the same key presses. In each task, the participants had to compare the relevant dimension of the first presented array with that of the second array. Unbeknown to the participants, the first array was always a standard array for which the value of the three dimensions never changed (i.e., 7 dots, 16 cm and 1000 ms). In the second array, the two irrelevant dimensions were manipulated in three different ways, so creating nine different experimental conditions. In the neutral conditions (N-N), only the relevant dimension, was manipulated while the two irrelevant dimensions were kept constant across stimuli (i.e., same values as the standard array) and could thus neither facilitate nor interfere with the judgement: the number of dots varied, but the duration and length were fixed (1000 ms and 16 cm) in the numerosity comparison; the length of the array varied but the numerosity and duration were fixed (7 dots and 1000 ms) in the length task; finally, the duration of the series varied but numerosity and length were fixed (7 dots and 16 cm) in the duration comparison. Next, the relevant dimension and one irrelevant dimension (say, Irrelevant dimension 1) were manipulated simultaneously, whereas the third dimension (say, Irrelevant dimension 2) was kept fixed to the neutral value. In this case, Irrelevant dimension 1 could be congruent (condition C-N) or incongruent (condition I-N) to the relevant dimension. Then, the

relevant dimension and Irrelevant dimension 2 were manipulated simultaneously in the same way, whereas Irrelevant dimension 1 was fixed to the neutral value (conditions N-C and N-I). Finally, the last four conditions were obtained by manipulating the three dimensions simultaneously. Stimuli in which the two irrelevant dimensions were congruent with the relevant dimension gave the congruent condition (C-C) and stimuli in which the two irrelevant dimensions were incongruent gave the incongruent condition (I-I). The two irrelevant dimensions could also have opposite values: one could be congruent and the other incongruent, and vice versa (giving conditions C-I and I-C).

The participants had to compare a 7-dot standard array with arrays containing 5, 6, 8 or 9 dots in the numerosity comparison task, a 16-cm standard array with arrays of 12, 14, 18 or 20 cm length in the length task, and a 1000-ms standard array with arrays lasting 700, 800, 1200 or 1300 ms in the duration comparison. Pairs of arrays made up each of the two distances used for each relevant dimension: a small distance (1 dot for numerosity, that is, pairs 6-7 and 7-8; 2 cm for length, that is pairs 14-16 cm and 16-18 cm; and 200 ms for duration, that is, pairs 800-1000 ms and 1000-1200 ms) and a large distance (2 dots for numerosity, that is, pairs 5-7 and 7-9; 4 cm for length, that is pairs 12-16 cm and 16-20 cm; and 300 ms for duration, that is, pairs 700-1000 ms and 1000-1300 ms). For the irrelevant dimensions, only the large distance was used (2 dots for numerosity, that is, pairs 5-7 and 7-9; 4 cm for length, that is pairs 12-16 cm and 16-20 cm; and 300 ms for duration, that is, pairs 700-1000 ms and 1000-1300 ms).

The stimuli were series of black dots of variable diameters and spacing, flashed one after another from left to right on a virtual horizontal line to constitute two different arrays for each trial. All the pairs of arrays were constructed using non-periodic signals so that temporal ratios did not constitute a potential confounding variable and rhythm biases and temporal pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; Dormal et al., 2006). The duration of each interdot (Di_j) varied between 75 and 320 ms; to avoid pattern recognition, each

array involved at least one Di_j of 75 ms and one longer than 250 ms, and each array ended with a Di_j of 50 ms (Figure 1a). To avoid spatial regularity biases, the spatial ratios were also controlled by applying similar principles (Dormal & Pesenti, 2007). The diameter of each dot (Le_j) and the interdot spacing (Li_j) varied from 0.25 to 2.5 cm; to avoid pattern recognition, each series involved at least one Le_j and on Li_j of 0.25 cm, and one Le_j and one Li_j greater than 2 cm (Figure 1b).

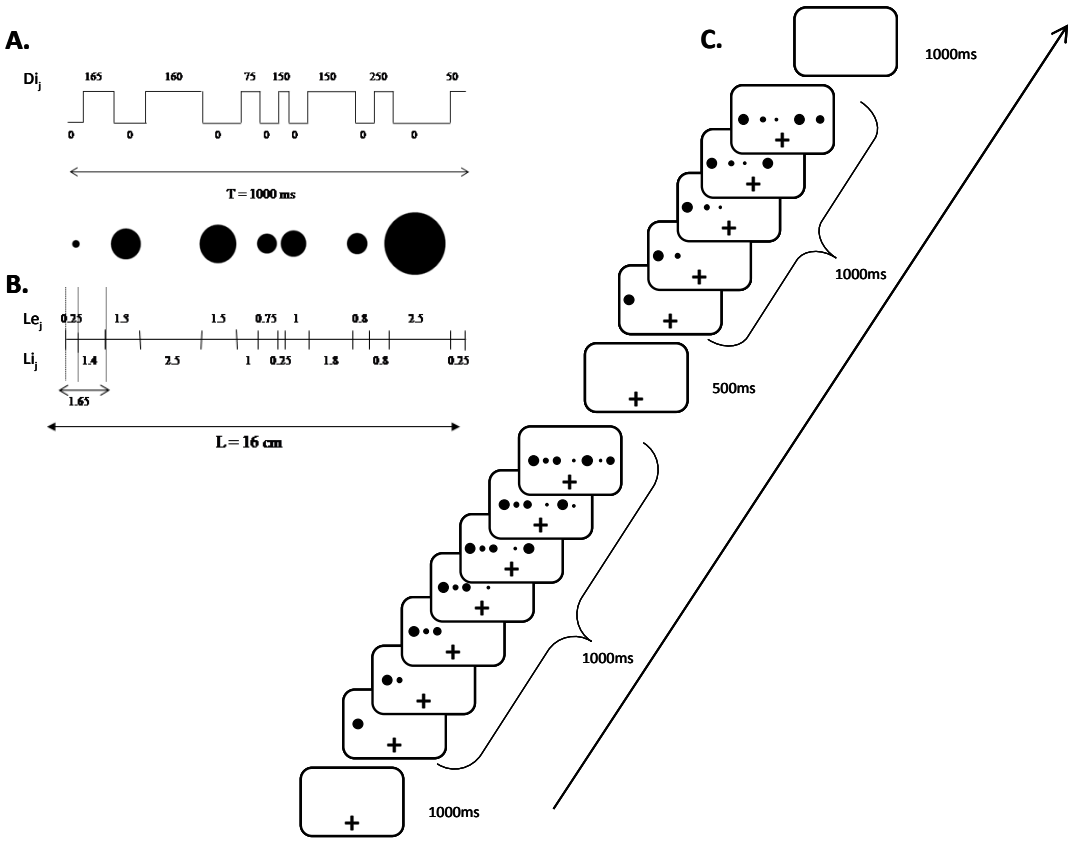

Figure 8.1: **(A)** Temporal attributes of the stimuli shown as a non-periodic standard series with 7 dots, a total duration of 1000 ms and a total length of 16 cm (T = Total signal duration; Di_j = interdot duration; see Dormal et al., 2006 for details). **(B)** Spatial attributes of the stimuli shown with the same example of a non-periodic standard series (L = Total length; Le_j = dot size; Li_j = interdot spacing; see Dormal & Pesenti, 2007 for details). **(C)** Temporal structure of one stimulus (here, one from the neutral condition of the numerosity task); each trial begin with a fixation cross for 1000ms, followed by two series of dots flashed one by one. After the removal of the second series, participants had 1000 ms to decide which series contained more dots, or was longer, or was presented for a longer duration as a function of the task.

To avoid comparisons based only on distance from the edge of the screen for the length comparison task, the arrays occupied five different positions on the screen: a central position

(30% from the left or the right edge of the screen), two intermediate positions (15% from the left or the right edge of the screen) and two extreme positions (7% from the left or the right edge of the screen).

3.3 Experimental procedure

Stimulus presentation and data collection were controlled by a Toshiba laptop using a customised E-prime programme (Schneider et al., 2002). The viewing distance was approximately 50 cm. At the beginning of each trial, a black fixation cross was presented horizontally in the centre and 5 cm below the vertical centre on a white background. This fixation crossed was present during the whole trial and disappeared after the presentation of the second series. After 1000 ms, the first array (i.e., the standard series) appeared, followed by a white background for 500 ms. Then, the second array was presented and was again followed by a white screen for a maximum of 1000 ms during which the participants could answer (Figure 1c). As soon as an answer was given, the next trial started. Each task was composed of 10 blocks of 54 randomized items; a practice block of 20 items was administered first but not analyzed. The whole experiment lasted about 50 minutes.

The instructions clearly requested the participants to focus on one of the dimensions and did not mention the other ones. The participants were told to look at the cross throughout the task to avoid as far as possible the use of explicit or implicit counting or enumeration strategies.

3. Results

3.1 Equivalence of the tasks and distance effect

To assess the equivalence of the three tasks and the presence of the relevant distance effects, an analysis of variance (ANOVA) was performed on the response latencies (RLs) of the correct answers in the three neutral conditions with tasks (numerosity, length or duration) as a between-subject variable and relevant distance (small or large) as a within-subject variable. There

was no difference between the tasks (mean RLs for numerosity: 407 ± 91ms, length: 471 ± 129 ms, duration: 439 ± 157 ms; $F(2,51)=1.128$, $p>.3$). A significant main effect was found for the relevant distance (mean RLs for small distances: 450 ± 136 ms, large distances: 428 ± 128 ms; $F(1,51)=7.447$, $p<.01$; Figure 2). No interaction was observed.

A similar ANOVA on error rates revealed no difference between the tasks (mean % error for numerosity: 13.3 ± 13.4, length: 17.2 ± 13.3, duration: 22.1 ± 9.1; $F(2,51)=2.388$, $p>.1$) but a significant main effect of the relevant distance (mean % error for small distances: 21.5 ± 11.4, large distances: 13.6 ± 15.3; $F(1,51)=31.9$, $p<.001$; Figure 2). No interaction was observed.

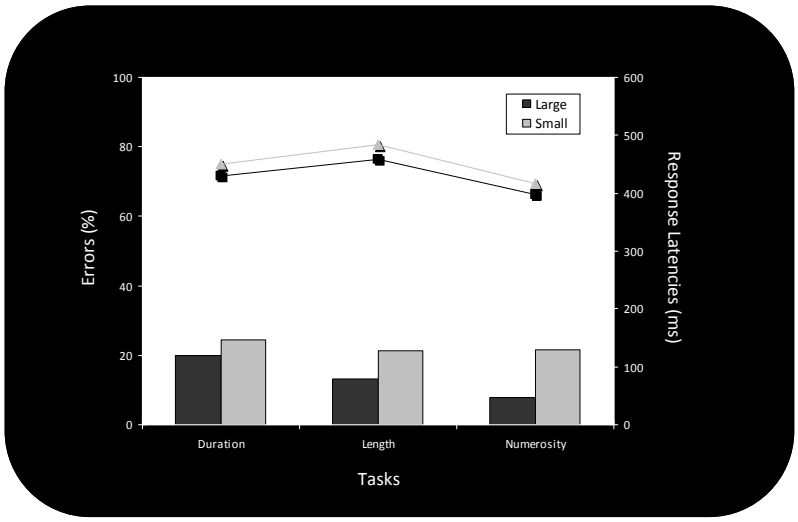

Figure 8.2: Mean percentage of errors and response latencies in ms for the duration, length and numerosity tasks as a function of the distance between arrays (small or large).

3.2 Interference and facilitation effects

To investigate the influence of the irrelevant dimensions on the relevant one, an ANOVA was carried out on the RLs of the correct answers with tasks (numerosity, length or duration) as a between-subject variable, and Irrelevant dimension 1 (congruent, incongruent or neutral) and Irrelevant dimension 2 (congruent, incongruent or neutral) as within-subject variables[24]. As a

[24] In separate analyses, the distance (small or large) was introduced as an additional within-subject variable. A main effect of distance on latencies (mean latency for small: 450 ± 119 ms; for large: 436 ± 115 ms; $F(1,51)=8.601$, $p>.006$) and on error rate (% of errors for small: 22.7 ± 9.7; for large: 14.9 ± 11.8; $F(1,51)=184.996$, $p>.001$) was found. In the

significant 3-way interaction between Irrelevant dimension 1, Irrelevant dimension 2 and task was observed ($F(8,204)=3.309$, $p<.001$), we report here the results of separate ANOVAs for the three tasks with Irrelevant dimensions 1 and 2 as within-subject variables. For the numerosity and length tasks, there were no significant main effects of the irrelevant dimensions nor interactions (all $p>.1$). For the duration task, a significant main effect of the numerical cues (i.e., Irrelevant dimension 1) was observed (mean RLs for congruent: 428 ± 135 ms, incongruent: 457 ± 140 ms, neutral: 428 ± 151 ms; $F(2,34)=10.672$, $p<.001$): the incongruent condition was processed more slowly than the congruent and neutral conditions (both $p<.001$). There was also a marginally significant effect of the spatial cues (i.e., Irrelevant dimension 2; mean RLs for congruent: 423 ± 145 ms, incongruent: 447 ± 133 ms, neutral: 443 ± 148 ms; $F(2,34)=2.783$, $p=.076$): the congruent condition was processed faster than the neutral and incongruent ones (both $p<.05$). Finally, an interaction between numerosity and length was found ($F(4,68)=7.543$, $p<.001$). Post-hoc paired *t*-tests showed a significant difference between the incongruent and the neutral conditions for numerosity only when length was incongruent (mean difference of RLs between I-I and N-I: 52.4 ± 68.1 ms; $t(17)=3.265$, $p<.005$). Conversely, for length, the neutral and congruent conditions differed only when the numerosity was incongruent (mean difference of RLs between I-C and I-N: 53.1 ± 60.2 ms; $t(17)=-3.744$, $p < .002$). The RLs of each condition were also compared to the N-N condition (corresponding to the baseline in which both irrelevant dimensions were kept constant) using paired *t*-tests to reveal the presence of facilitation and/or interference effects. A significant slowing down of RLs was only observed when numerosity was incongruent (mean difference of RLs between I-N and N-N: 40.9 ± 65.8 ms, $t(17)=2.637$, $p=.017$).

The same ANOVA was performed on the mean percentage of errors. This revealed a significant 3-way interaction between Irrelevant dimension 1, Irrelevant dimension 2 and tasks ($F(8,204)=15.712$, $p<.001$; Figure 3). Separate ANOVAs for the three tasks were carried out with

error rate analysis, this variable entered into some interactions but, as it never changed the direction of the main effect of other factors, it was not included in the main analysis.

Irrelevant dimensions 1 and 2 as within-subject variables. For the numerosity task, no main effect was observed but a significant interaction was present ($F(4,68)=5.214$, $p<.001$). A significant difference between the congruent and neutral conditions for length only occurred when duration was incongruent (mean difference of % between C-I and N-I: 7.9 ± 13.6; $t(17)=-2.457$, $p<.03$). Post-hoc paired *t*-tests between the mean error rate of each condition and N-N revealed only marginally significant differences for N-I and I-I conditions (mean difference of % between N-I and N-N: 4.54 ± 10.24; $t(17)=1.880$, $p=.077$; between I-I and N-N: 3.89 ± 9.32, $t(17)=1.769$, $p=.095$; Figure 4): participants made more errors when either the length or both the irrelevant dimensions were incongruent.

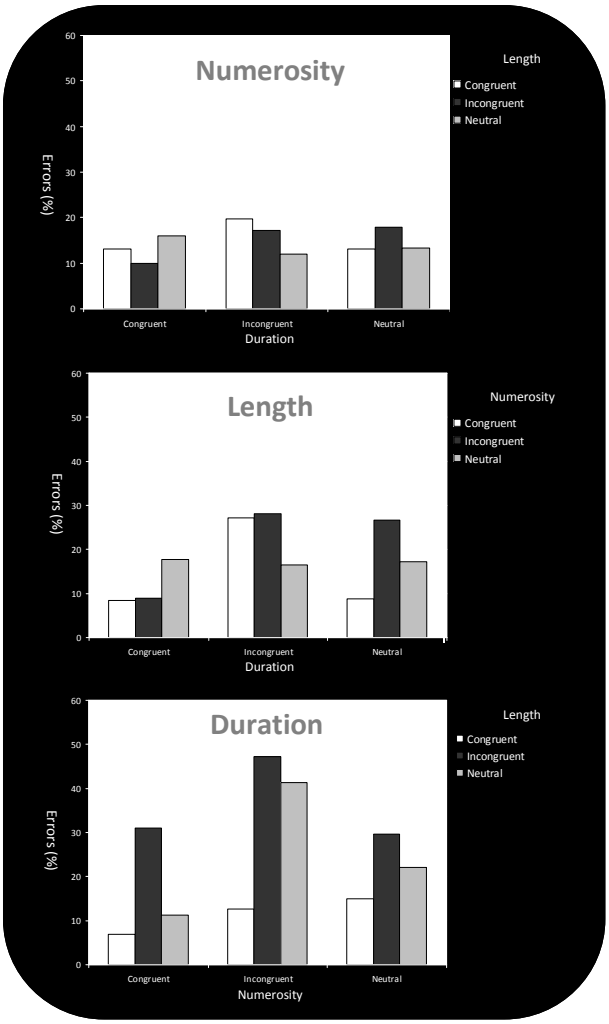

Figure 8.3: Mean percentage of errors for duration, length and numerosity tasks as a function of Irrelevant dimensions 1 and 2 (congruent, incongruent or neutral).

For the length task, significant main effects of numerosity (i.e., Irrelevant dimension 1; $F(2,34)=15.270$, $p<.001$) and of duration (i.e., Irrelevant dimension 2; $F(2,34)=9.842$, $p<.001$) were found. For numerosity, all the conditions differed significantly from each other (mean % errors for congruent: 11.7 ± 8.6, incongruent: 23.9 ± 18.6, neutral: 17.5 ± 14.0; congruent-neutral: $t(17)=-3.546$, $p<.002$; incongruent–neutral: $t(17)=4.035$, $p<.001$; congruent-incongruent: $t(17)=-3.971$, $p=.001$). For duration, the congruent condition differed marginally from the neutral condition (mean % errors for congruent: 14.7 ± 11.3, neutral:17.12 ± 12.7; $t(17)=-2.057$, $p=.055$) and the incongruent condition differed significantly from the neutral (mean % of errors for incongruent: 21.2 ± 17.1; $t(17)=2.914$, $p<.010$) and from the congruent condition ($t(17)=-3.607$, $p<.002$). The interaction between numerosity and length was also significant ($F(4,68)=9.942$, $p<.001$). A significant difference between the neutral and incongruent conditions for duration was only observed when numerosity was congruent (mean difference of % between N-C and I-C: 18.4 ± 22.0; $t(17)=3.550$, $p<.002$) whereas a significant difference between the congruent and neutral conditions occurred when numerosity was incongruent (mean difference of % between C-C and N-C: 17.7 ± 21.5; $t(17)=-3.487$, $p<.003$). Moreover, the results showed that participants made fewer errors when the numerosity or both the irrelevant dimensions were congruent (mean difference of % between N-C and N-N: -8.52 ± 12.19; $t(17)=-2.964$, $p<.009$; between C-C and N-N: -8.80 ± 11.82; $t(17)=-3.156$, $p<.006$). In the same way, participants made more errors when numerosity or both the irrelevant dimensions were incongruent (mean difference of % between N-I and N-N: 9.35 ± 12.18; $t(17)=3.257$, $p<.005$; between I-I and N-N: 10.93 ± 11.68; $t(17)=3.970$, $p<.001$; Figure 4).

Finally, for the duration task, the results showed significant main effects of numerosity (i.e., Irrelevant dimension 1; $F(2,34)=46.994$, $p<.001$) and length (i.e., Irrelevant dimension 2; $F(2,34)=88.614$, $p<.001$). For both main effects, post-hoc paired sampled t-tests showed that all conditions differed significantly from each other (Numerosity mean % of errors for congruent:

16.4 ± 6.9, incongruent: 33.7 ± 11.7, neutral: 22.3 ± 9.0; Length mean % of errors for congruent: 11.5 ± 6.0, incongruent: 36.0 ± 11.7, neutral: 24.9 ± 9.9; all p<.001). Moreover a significant interaction between numerosity and length was found (F(4,68)=21.016, p<.001). When numerosity was congruent, no difference between incongruent and neutral condition for length was observed (mean difference of % between C-I and C-N: 2.4 ± 7.1; t(17)=-1.444, p>0.1). Conversely, when numerosity was incongruent, there was no significant difference between the congruent and neutral conditions for length (mean difference of % between I-C and I-N: 1.3 ± 12.0; t(17)=0.458, *ns.*). Finally, the participants made fewer errors when numerosity or length or both were congruent (mean difference of % between C-N and N-N: -10.83 ± 8.62; t(17)=-5.333, p<.001; between N-C and N-N: -7.13 ± 9.53; t(17)=-3.175, p<.006; between C-C and N-N: -15.19 ± 9.75; t(17)=-6.608, p<.001). Similarly, all the incongruent conditions were significantly different from N-N (mean difference of % between I-N and N-N: 19.17 ± 11.62; t(17)=6.998, p<.001; between N-I and N-N: 7.59 ± 8.73; t(17)=3.690, p<.002; between I-I and N-N: 25.09 ± 14.21; t(17)= 7.494, p<.001; Figure 4): a significant increase in the error rate was observed when numerosity, or length or both were incongruent.

4. Discussion

In this study, we investigated for the first time the reciprocal interference effects of numerosity, length and duration. We will first discuss the interference of each dimension individually, that is, the experimental conditions in which only one of the two irrelevant dimensions was manipulated. Then, we will comment on the joint influence of the two irrelevant dimensions and, where relevant, the interaction between these two dimensions and the relevant one. It is important to note that, in the selected range of numerosities, lengths and durations, the participants were equally fast and accurate on all three comparison tasks in the neutral condition. So, the observed differences cannot be due to differences in the relative speed of processing each dimension individually, or in the attentional or difficulty demands across tasks. Moreover, a

classic effect of the relevant distance (Moyer & Landauer, 1967) was observed in all tasks, ensuring that the participants actually performed the comparisons using the appropriate dimension (i.e., numerosity in the numerosity comparison, length in the length comparison, and duration in the duration comparison).

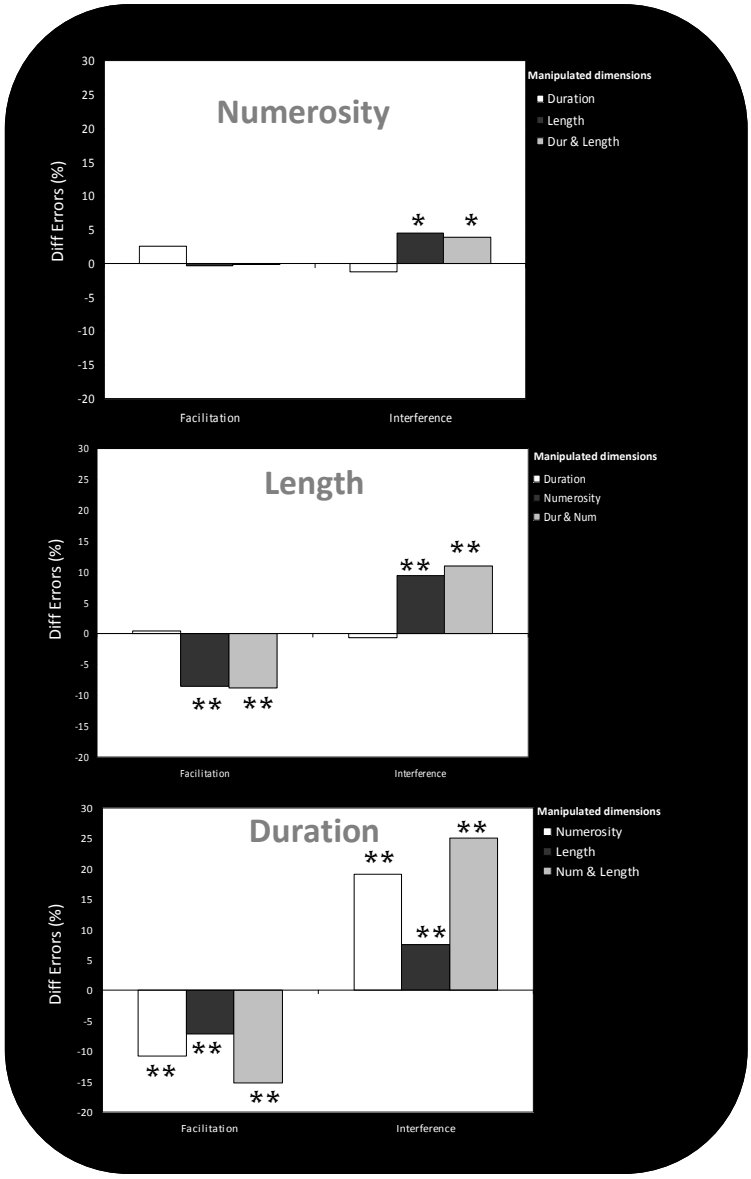

Figure 8.4: Difference in the mean percentage of errors for each condition relative to the neutral condition for duration, length and numerosity tasks as a function of effect's direction (facilitation or interference) and the dimensions manipulated (Irrelevant dimension 1, 2 or both). Asterisks indicate which conditions were significantly different from zero (**: p<.05, *: .05 < p > .1).

4.1 Unidimensional and bidimensional effects

The conditions in which only one irrelevant dimension was manipulated, the second one remaining neutral, allowed us to explore the distinct influence of each dimension on the others. In the numerosity comparison task, an irrelevant variation in length only had a weak influence, and an irrelevant variation in duration had no significant effect on the numerosity comparison. Performance in the length comparison task was affected by variations in numerosity: incongruent numerical cues interfered with length judgements whereas congruent numerical cues facilitated them. No such effect on length estimation processing due to temporal cues was observed . Finally, in the duration comparison task, both numerosity and length interfered strongly with duration. Independent interference and facilitation effects of numerical and spatial dimensions were observed for error rates in duration comparison, with participants making fewer errors in the congruent condition and more errors in the incongruent condition than in the neutral condition.

The present study thus shows a unilateral interaction effect between numerosity and duration, similar to that reported in previous studies (Dormal et al., 2006; Droit-Volet et al., 2003; Roitman et al., 2007): numerical cues interfered strongly with duration processing, whereas temporal cues did not affect numerosity processing. It also shows, for the first time with this kind of non-symbolic stimuli, an asymmetric pattern of interaction between length and duration. In the duration comparison, there were both facilitation and interference effects of length on error rates (fewer errors in the congruent condition, and more errors in the incongruent condition, than in the neutral one); conversely, in the length comparison task, no difference between the three duration conditions (i.e., congruent, congruent and neutral), was observed on either response latencies or error rates, suggesting that the temporal cues did not influence the length judgement. Like the kappa effect described in psychophysical studies (Cohen et al., 1953), this interference of length cues on duration processing reflects an implicit and automatic processing

of the spatial dimension, in a context where length does not have to be processed to carry out the task. Numerical and spatial dimensions demonstrated a reciprocal influence, confirming the results reported in various other studies of interference (e.g., Pufall & Shaw, 1972; Henik & Tzelgov, 1982; Dormal & Pesenti, 2007). However, unlike previous studies (e.g., Dormal & Pesenti, 2007), we found that the numerical influence on length judgements was stronger than the spatial influence on numerosity comparisons. Differences in the experimental design may explain this discrepancy. In our study, sequential presentation forced the participants to focus their attention on each individual dot display in order to judge the total length of the arrays. This individuation process could have automatically activated an accumulation mechanism (Dehaene & Changeux, 1993; Meck & Church, 1983), leading to greater salience for the numerical cues. Inversely, individual processing of each element is not necessary to grasp the total length when the elements are presented simultaneously, and so numerosity does not interfere strongly with length judgments, whereas the spatial extent is necessarily processed when judging the total numerosity of an array of dots. This may explain why length cues interfere with simultaneous numerosity judgements (Dormal & Pesenti, 2007).

4.2 Continuum of automaticity

Taken together, the patterns of performance in these comparison tasks point towards two important conclusions. Firstly, numerosity seemed to be highly automatically processed, as shown by its strong interference effect on duration and length judgements. This fits with previous results using both non-symbolic (Dormal et al., 2006; Koechlin et al., 1999; Piazza et al., 2004), and symbolic (e.g., Arabic or verbal numerals; Algom et al., 1996; Henik & Tzelgov, 1982) stimuli. Secondly, duration processing is not sufficiently automatic to interfere with the processing of other magnitudes, but the duration judgements are vulnerable to the influence of both numerosity and length. As the overall performance did not differ across tasks, these asymmetrical interference patterns support the existence of a continuum of automaticity in processing

numerosity, length and duration, with numerosity being the most and duration the least automatic. It is important to note that this continuum may be dependent on the range, the modality (i.e., visual) and mode (i.e., sequential or simultaneous) of presentation, and the experimental design chosen (i.e., Stroop comparison) in this series of experiments. Other studies with a larger range of stimuli, different materials and tasks are thus needed to explore this idea more generally.

Chapitre 9

Mode-dependent and mode-independent representations of numerosity in the right intraparietal sulcus

Ce chapitre constitue une version légèrement modifiée de l'article portant le même titre, par Dormal, Andres, Dormal & Pesenti (soumis).

1. Abstract

In the parietal cortex of monkeys, some populations of neurons were found to respond selectively to sequentially- or simultaneously-presented numerosities, whereas other populations showed similar activation in both modes of presentation. However, whether such mode-dependent and -independent representations of numerosity also exist in humans is still unknown. Here, we used fMRI to identify the areas involved in numerosity processing while participants classified linear arrays of dots (simultaneous stimuli) or flashed dot sequences (sequential stimuli). The processing of simultaneous numerosities induced activations bilaterally in several areas of the intraparietal sulcus (IPS), whereas activations during the processing of sequential numerosities were restricted to the right hemisphere. A conjunction analysis showed that only the right IPS and precentral gyrus showed overlapping activations during the judgement of sequential and simultaneous stimuli. Voxelwize correlations confirmed the highly similar pattern of activation found in these regions during both tasks. This pattern was weaker or absent in mode-dependent regions, like the right inferior frontal cortex and the lateral occipital complex. Finally, a close look at the right IPS revealed an anterior-to-posterior gradient of activation with selective activation for sequential and simultaneous stimuli in the anterior and posterior areas, respectively, and overlapping activations in-between. This study provides the first direct evidence that, in humans, the right IPS contains both mode-dependent and mode-independent representations of numerosities.

2. Introduction

Humans shared with animals the early ability of estimating numerosity in a nonverbal non symbolic way (i.e., approximate quantification system), constituting the precursor of more elaborate numerical skills (Halberda, Mazzocco & Feigenson, 2008; Nieder & Dehaene, 2009; Piazza & Izard, 2009). Involvement of the IPS in the processing of non symbolic numerical magnitudes (i.e., number of elements in a collection) is well established in humans. Indeed, activation of the left and right IPS was reported in response to deviant numerosities when participants were passively exposed to arrays of dots or squares in habituation paradigms (Cantlon et al., 2006; Piazza et al., 2004; 2007). Bilateral involvement of the IPS has also been demonstrated in dot comparison (Dormal & Pesenti, 2009), dot enumeration (Fink et al., 2001; Piazza et al., 2002; 2003; Sathian et al., 1999), and non symbolic simple addition tasks (Venkatraman et al., 2005). Modulation of activation as a function of the distance of the to-be-compared numerosities, which has been observed in bilateral parietal areas during comparison tasks in electrophysiological (Libertus, Woldorff & Brannon, 2007) and fMRI (Ansari & Dhital, 2006) studies, provides additional support to the critical role of these regions in non symbolic numerosity processing. Finally, two recent transcranial magnetic stimulation (TMS) studies showed that the comparison of dot collections was slowed down after left IPS stimulation when stimuli were presented sequentially (Dormal et al., 2008) or simultaneously (Cappelletti et al., 2007), but was not affected after right IPS or control stimulation.

Several studies have shown that the same IPS area is involved in both non symbolic and symbolic numerical processing. For example, in the aforementioned TMS study (Cappelletti et al., 2007), the interference effect found when comparing patterns of dots after left IPS stimulation was also observed with Arabic digits. Recent fMRI adaptation (fMRA) studies showed an adaptation of the BOLD signal in the IPS in response to numerosity repetition, irrespective of notation (i.e., Arabic digits or sets of dots: Piazza et al., 2007; Arabic digits or number words:

Cohen Kadosh et al., 2007), which confirms previous findings using other methods (e.g., ERP and fMRI: Pinel et al., 2001). Therefore, it is reasonable to assume that the IPS contribution to number magnitude processing is *notation-independent*, as evidenced by common activation in response to numbers of elements, Arabic and verbal numerals (Ansari, 2007; Cantlon et al., 2009), and *modality-independent*, as visual and auditory numerosity processing were associated to similar neural codes in the IPS (Eger, Sterzer, Russ, Giraud & Kleinschmidt, 2003; Piazza et al., 2006).

These results have led to the hypothesis that the IPS hosts a core representation of numerosity which is invariant with respect to the symbolic or non symbolic format of presentation, available spontaneously in infants and shared with other species (Dehaene et al., 2003; Piazza & Izard, 2009). Whereas those characteristics are supported by a large amount of brain imaging data, the influence of the spatial or temporal structure of the stimuli on numerosity processing has received little interest in the human neuroimaging literature. If the IPS plays a central role in the representation of numerosity, it should be recruited similarly to estimate a collection of stimuli presented simultaneously or a number of sequential events. It is therefore crucial to determine whether the numerical contribution of the IPS is rooted to spatial perception or whether it can extend to the processing of temporal series.

Electrophysiological recordings in the monkey brain have demonstrated that number-sensitive neurons in the IPS can show different responses according to the presentation mode (Nieder et al., 2006). Some neurons were found to be tuned selectively by sequentially presented numerosities, whereas the same numerosities recruited other neurons when they were presented simultaneously, supporting the existence of distinct mechanisms for the parallel or sequential extraction of numerosity. A third class of neurons was found to discharge whether numerosity had been presented sequentially or simultaneously; these neurons were assumed to encode the final result of the quantification process irrespective of its mode of presentation.

In humans, such a functional subdivision of the IPS areas involved in numerosity processing has never been reported. One previous fMRI study used both sequential and simultaneous presentations but, because the goal of the study was not to compare presentation modes, only common activations were reported (Castelli et al., 2006). Participants had to judge whether there was more blue or more green in discrete or continuous displays changing either in space (a single rectangle filled with blue and green hues, corresponding to simultaneous presentation) or in time (temporal sequences of blue and green squares, corresponding to sequential presentation). A greater bilateral activation of the IPS was reported during discrete compared to continuous quantity comparison, both in space (simultaneous) and in time (sequential). However, these data are inconclusive regarding the effect of the presentation mode since the overlap and/or dissociations between the IPS areas recruited during simultaneous and sequential presentations were not assessed.

The functional segregation of the brain areas related to each presentation mode raises two additional challenges. First, it is necessary to design the stimuli very carefully in order to exclude any covariation between numerical and nonnumerical variables, such as the surface covered by the stimuli or the duration of the display. Second, the range of numerosities and the presentation time need to be calibrated appropriately to prevent the use of counting strategies by the subject. Indeed, using of counting strategies may bias the study of the core numerical abilities, because counting abilities are effortful, culturally-defined and rely on additional brain networks relative to those involved in the estimation of numerosities (Demeyere & Humphreys, 2007; Gordon, 2004; Piazza et al., 2006; Pica, Lemer, Izard & Dehaene, 2004).

The present fMRI study aimed at solving these issues to provide the first detailed investigation of the pattern of activations induced by sequential or simultaneous presentations of numerosities. Participants had to categorize as “few” or “many” the numerosity of linear arrays of dots (i.e., Simultaneous Numerosity categorization, hereafter SimN) or of flashed dot sequences

(i.e., Sequential Numerosity categorization, hereafter SeqN). If the same numerosity representation underlies the processing of these two presentation modes, then common activations should be observed, most likely in the parietal areas usually involved in numerosity processing. Importantly, using simultaneous and sequential stimuli in the same experiment provides a direct test of the core numerosity representation by excluding the spatial and temporal components most often intrinsically involved in numerosity processing.

In a first step, we performed a whole-brain analysis to see whether the distinct and common neuronal populations found in the monkey brain during similar tasks, could be observed at a macroscopic level in humans. In a second step, in order to specify the relationship between the parietal networks dedicated to simultaneous and sequential numerosity processing, we measured voxelwize correlations between the index of activation computed for each critical site. The rationale is that the overlapping activations revealed by fMRI may reflect spatial blurring or intermingled but functionally independent brain networks. In this case, the probability to observe similar variations of the fMRI signal across the voxels commonly activated by the two tasks is weak and a null or negative correlation is expected (Downing, Wiggett & Peelen, 2007; Peelen, Wiggett & Downing, 2006; Peelen & Downing, 2007a; Peelen & Downing, 2007b; Peelen, Atkinson, Andersson & Vuilleumier, 2007). Alternatively, a positive correlation would suggest a functional dependency between the patterns of activation induced by simultaneous and sequential presentations. Indeed, if the overlap of the voxels activated by the two tasks follows functional lines, the peak voxels in one task should also exhibit the highest signal in the other task, and the less activated voxels in one task should be weakly activated in the other task as well. The quantitative assessment of task correlations across voxels should help us to address functional hypotheses while taking into account intrinsic biases in the processing of fMRI images. However, the spatial resolution of the fMRI is far from the one obtained with invasive electrophysiological recordings in monkeys. The multi-voxel pattern analysis should therefore be regarded as a way to

specify the functional relationship between the patterns of activation observed in the two tasks at the level of 2-mm voxels, which was the highest spatial resolution available in the present study, but not as a tool to replicate the finding of common neuronal populations in neurophysiological studies. Finally, we performed a voxelwize analysis of the activations found along the right IPS to specify the anatomical landmarks delineating the subdivision of the areas involved in sequential and simultaneous presentations. It is well known, for example, that the substrate of spatial processing extends in the posterior segments of the IPS, whereas the core numerosity representation has been located in the anterior horizontal segment of the IPS (Dehaene et al., 2003; Simon et al., 2002).

2. Method

2.1 Participants

Fifteen healthy, French-speaking, male volunteers (mean age: 21 ± 2.3 years) participated in this study after giving their informed written consent. All the participants were right-handed as attested by the Edinburgh inventory questionnaire (Oldfield, 1971), had no history of neurological or psychiatric disorders, had corrected-to-normal vision, and were unaware of the purpose of the study. The experiment was non-invasive and was performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration; the experimental protocol was approved by the Biomedical Ethical Committee of the Université catholique de Louvain.

2.2 Tasks and stimuli

Two categorization tasks were used: (1) a numerosity categorization of linear arrays of dots presented simultaneously (SimN) and (2) a numerosity categorization task of sequences of dots (SeqN). In each task, the participants had to decide if the arrays/sequences contained "few" (i.e., 6) or "many" (i.e., 8) dots by pressing a left- or right-hand response button on a response box.

To prevent, as far as possible, potential explicit or implicit counting strategies, nonsubitizable numerosities were presented very briefly. In the SimN task, the stimuli were composed of linear arrays of 6 or 8 black dots presented for 200 ms (Figure 9.1A). Non-periodic signals were used so that spatial ratios were not confused with numerosity (for more details, see Dormal & Pesenti, 2007). The total length of the arrays remained constant (10 cm), while the diameter of each dot (Le_j) and the interdot spacing (Li_j) varied from 3.3 to 15 mm. To avoid pattern recognition, each series involved at least one Le_j and one Li_j of 3.3 mm and one of 15 mm. In the SeqN task, the stimuli were composed of a black dot (diameter: 3.5 cm) flashed rapidly in the center of the screen (Figure 9.1C).

The sequences contained 6 or 8 dots and were constructed using non-periodic signals so that temporal ratios did not constitute a potential confounding variable, and rhythm biases and pattern recognition were avoided (for more details, see Breukelaar & Dalrymple-Alford, 1998; Dormal et al., 2006). The total duration of the sequences was constant (1800 ms), while the duration of each dot presentation (De_j) and the duration of the interdot interval (Di_j) varied from 50 to 270 ms. To avoid pattern recognition, each series involved at least one De_j and one Di_j of 50 ms and one De_j and one Di_j longer than 200 ms; each sequence began and finished with an Di_j of 50 ms. The reference tasks were composed of the same stimuli as those in the corresponding experimental tasks except that the array of dots was presented in red in half of the SimN stimuli, and the last dot of each sequence was colored in red in half of the SeqN stimuli. Participants were required to indicate whether the array/last dot was colored or not. These reference tasks were equated with the experimental tasks in terms of visual complexity and manual forced-choice responses.

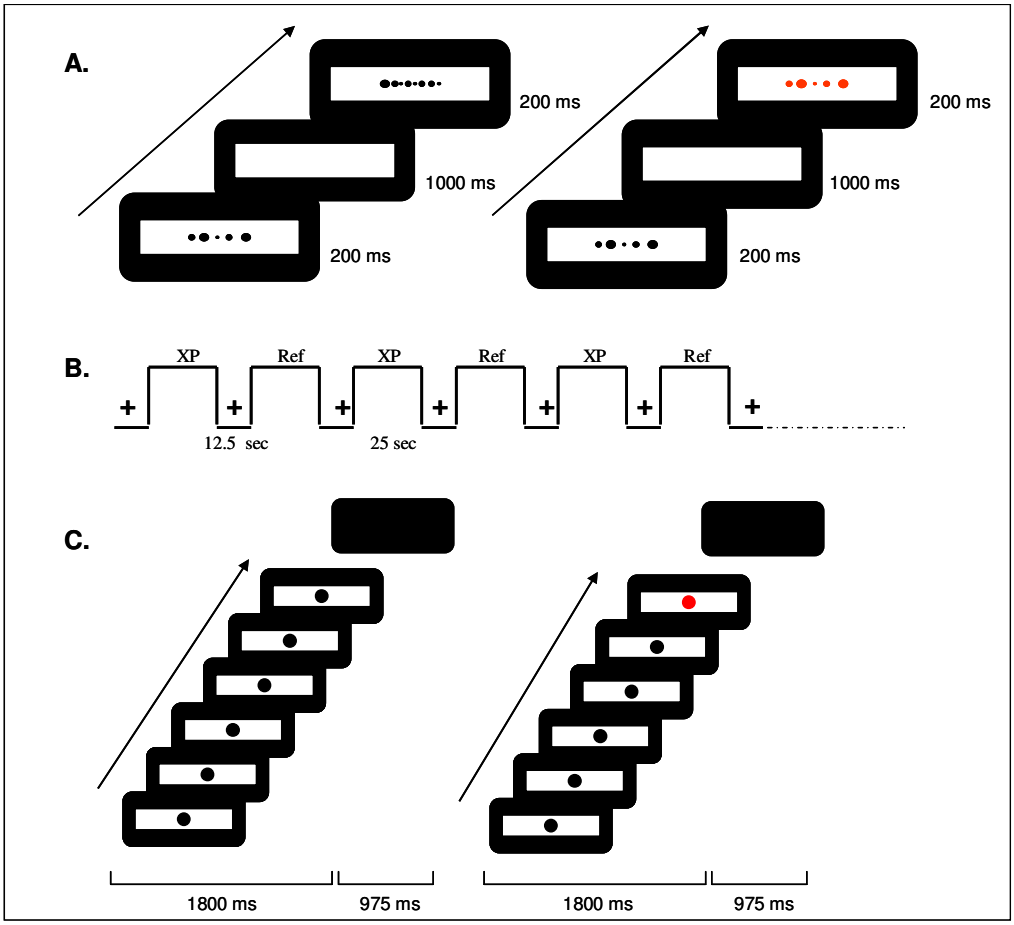

Figure 9.1: Schematic representation of the temporal structure of the experiment**. (A)** Examples of simultaneous numerosity experimental (left) and reference (right) task: each trial was composed of a stimulus (a linear arrays of dots) displayed for 200 ms, and a blank response screen for 1000 ms. For the reference task, the array was either black or red. **(B)** fMRI design. Each run consisted of 10 alternations of a 12.5-sec fixation period (black cross on white background) and a 25-sec activation period. Each activation period corresponded to either an experimental condition or its reference condition. **(C)** Examples of sequential numerosity experimental (left) and reference (right) task: each trial was composed of a stimulus (a flashed dots series) displayed for 1800 ms, and a blank response screen for 975 ms. For the reference task, the last dot of the series was either black or red.

2.3 Experimental procedure

Before the fMRI experiment, each participant underwent, for each task separately, a preliminary training session outside the magnet room, which included a learning block, a training block with feedbacks, and an example of an fMRI acquisition run. In the learning block, 20 examples of arrays/sequences with few and many dots were presented and the participants were instructed to observe carefully; the numerosity of the arrays/sequences was never mentioned.

During the training block, randomized trials were presented and the participant had to categorize each of them as containing "few" or "many" dots by pressing one of two keys on the numerical pad (key 1 with the right index finger for arrays/sequences with few dots, key 3 with the right ring finger for arrays/sequences with many dots). After each answer, a visual feedback indicated whether the answer was correct or not. Finally, four blocks (2 blocks of an experimental task alternating with 2 blocks of the corresponding reference task) without feedback were administered to familiarize the participants with the procedure used during the fMRI study.

In the magnet room, back-projected images were viewed through a tilted mirror mounted on the head coil, and the participants answered by pressing a 2-button response pad with the index of their left or right hand for "few" and "many" answers, respectively; the projector and the mirror (Silent Vision™ System, Avotec, Inc., <http://www.avotec.org>) and the response pad (Imagilys, <http://www.imagilys.com/>) were compatible with the MRI environment. Stimulus presentation and response recording were controlled with E-Prime (Schneider et al., 2002). Each participant underwent four acquisition runs in a counterbalanced order (i.e., ABBA or BAAB): two runs of 5 blocks of the SimN task alternating with 5 blocks of the corresponding reference task, and two runs of 5 blocks of the SeqN task alternating with 5 blocks of its reference task. These 10 blocks lasted 25 sec and were interleaved with 12.5 sec-fixation periods (black cross on white background) (Figure 9.1B). Before each run, two blocks of examples of arrays/sequences with “few” and “many dots” respectively were presented as a reminder of the categorization rules.

2.4 fMRI acquisition and analysis

Functional images were acquired with a 3.0 Tesla magnetic resonance imager and an 8-channel phased array head coil (Achieva, Philips Medical Systems) as series of blood-oxygen-sensitive T2*-weighted echo-planar image volumes (GRE-EPI). Acquisition parameters were: TE = 32 ms, TR = 2500 ms, Flip angle = 90°, Field of view = 220 x 220 mm, slice thickness = 3.5 mm with no interslice gap, SENSE factor (parallel imaging) = 2.5. Each image volume comprised 36 axial

slices acquired in an ascending interleaved sequence. High-resolution anatomical images were also acquired for each participant using a T1-weighted 3D turbo fast field echo sequence with an inversion recovery prepulse (150 contiguous axial slices of 1 mm, TE = 4.6 ms, TR = 9.1 ms, Flip angle = 8°, FOV = 220 x 197 mm, voxel size = 0.81 x 0.95 x 1 mm3, SENSE factor = 1.4). Head movement was limited by foam padding within the head coil and a restraining band across the forehead.

Data were processed and analyzed using Statistical Parametric Mapping (SPM2, Welcome Department of Cognitive Neurology, London, UK, <http://www.fil.ion.ac.uk/spm>). Functional images were (1) corrected for slice acquisition delays, (2) realigned to the first scan of the first run (closest to the anatomical scan) to correct for within- and between-run motion, (3) coregistered with the anatomical scan, (4) normalized to the MNI template using an affine fourth degree ß-spline interpolation transformation and a voxel size of 2 x 2 x 2 mm^3 after the skull and bones had been removed with a mask based on the individual anatomical images, and (5) spatially smoothed using a 10-mm FWHM Gaussian kernel.

Condition-related changes in regional brain activity were estimated for each participant by a general linear model in which the responses evoked by each condition of interest were modeled by a standard hemodynamic response function. The contrasts of interest were first computed at the individual level to identify the cerebral regions significantly activated by sequential and simultaneous numerosity, relative to the fixation periods used as a general baseline (respectively, *[SeqN – fix],* and *[SimN – fix]*), and similarly for each reference task. Significant cerebral activations for the critical contrasts (experimental task *minus* reference task, each relative to the fixation periods) were then examined at the group level in random-effect analyses using one-sample *t*-tests and ANOVAs with the statistical threshold set at $p<.05$ (FWE corrected at the voxel level) and extending to at least 60 contiguous voxels (k). Given the strong *a priori* hypotheses, activations in the parietal cortices were also screened at lower, uncorrected thresholds. The conjunction (using

the Minimum Statistic compared to the Conjunction Null, MS/CN; Nichols et al., 2005) of the two experimental contrasts with their own reference contrast isolated the cerebral activations elicited in common by sequential and simultaneous numerosity categorization. Then, to assess the selectivity of activations observed in this conjunction, we performed a multi-voxel correlation analysis (Downing et al., 2007; Peelen et al., 2006). First, five functional regions of interest (ROIs) were defined based on the results of the conjunction analysis and the critical contrasts of each experimental task with its reference: the right IPS and the right precentral gyrus from the conjunction, the right frontal gyrus from the SeqN task, and the bilateral temporo-occipital junction from the SimN task. The frontal and occipital sites activated only in sequential and simultaneous numerosity respectively were chosen as control sites. These ROIs were then intersected with a 5-mm-radius sphere, with the center of the sphere at the peak of the relevant contrast. For a 5-mm sphere, the maximum number of voxels in each ROI was 81 voxels. The *t*-value for each voxel within a given ROI was then extracted from the unsmoothed normalized and resampled images of the two contrasts of interest (*[SeqN – RefSeqN]*, and *[SimN – RefSimN]*). For each participant, the voxel-by-voxel correlation between *t*-values within the ROI defined by the group conjunction was calculated. The mean correlation across participants was then calculated, and its significance tested using a one-sample *t*-test against zero. Finally, in order to quantify the extent of the IPS activation corresponding to each task and to determine the subregions specifically implicated, we computed an anterior-posterior index over the right IPS region (Figure 9.3C). This index was obtained by averaging the contrast-weighted *t*-values for the comparison of each experimental task versus its own reference task along the medial-to-lateral (x) and superior-to-inferior (z) dimensions. The anterior-posterior index was calculated for SimN and SeqN tasks.

3. Results

3.1 Behavioral data

An analysis of variance (ANOVA) was performed on the response latencies (RLs) of correct

answers with condition (Experimental *vs.* Reference) and presentation (SimN *vs.* SeqN) as within-subject variables. Significant main effects of condition ($F(1,14)=39.461$, $p<.001$) and presentation ($F(1,14)=51.874$, $p<.001$) were observed. Participants responded faster overall in the reference (283 ± 53 ms) than in the experimental (346 ± 47 ms) conditions, and faster when the task used simultaneous (267 ± 51 ms) compared to sequential (362 ± 55 ms) presentation. Moreover, RLs showed a condition by presentation interaction ($F(2,13)=8.350$, $p<.02$): the difference between the experimental and reference tasks was larger for simultaneous (experimental: 311 ± 53 ms, reference: 223 ± 58 ms, difference: 88 ± 47 ms; $t(14)=7.378$, $p<.001$) than for sequential (experimental: 380 ± 67 ms, reference: 343 ± 57 ms, difference: 37 ± 57 ms; $t(14)=2.551$, $p<.03$) presentation (Figure 9.2).

A similar ANOVA on error rates revealed a significant main effect of condition only ($F(1,14)= 20.302$, $p<.001$), with participants making more errors in experimental (10 ± 5%) than in reference (3 ± 2%) conditions (Figure 9.2). No other main effect or interaction was significant.

3.2 Functional data

3.2.1 Simultaneous numerosity processing

Contrasting the SimN task to its reference revealed a large focus of activation in the right inferior parietal lobule, in the depth of and around the IPS. Other activation foci were found bilaterally in the inferior temporal gyri and in the right precentral gyrus (Table 9.1a and Figure 9.3A). At an uncorrected threshold ($p<.001$), activations were observed in the left inferior and superior parietal lobules along the posterior part of the IPS. Contrasted to SeqN, the SimN task revealed left-lateralized occipital and cingular activations. Foci of activation were also observed bilaterally in the precuneus (Table 9.1c).

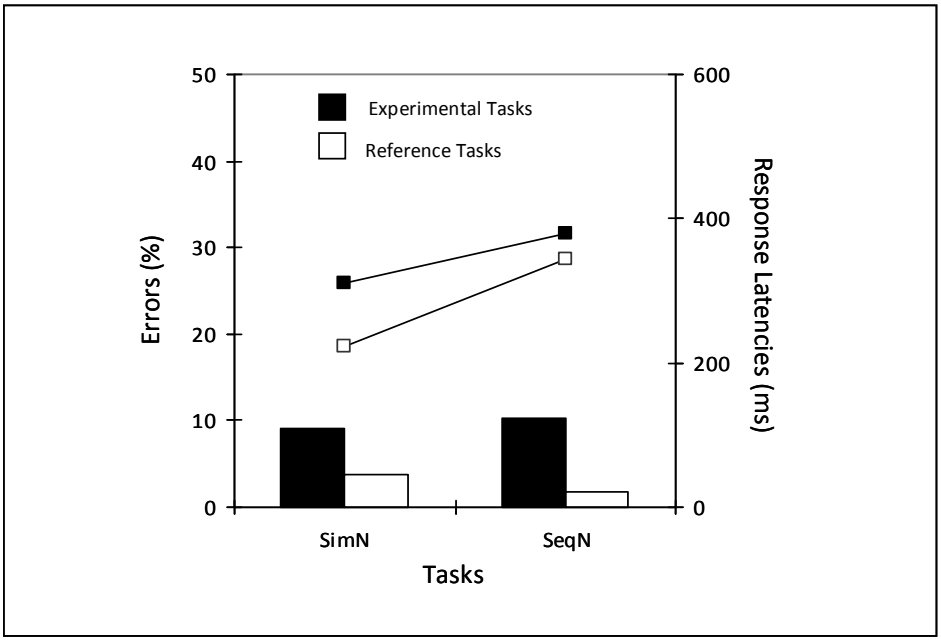

Figure 9.2: Mean percentage of errors and response latencies in milliseconds for simultaneous and sequential numerosity categorization tasks (SimN *vs.* SeqN), as a function of the condition (experimental *vs.* reference).

3.2.2 Sequential numerosity processing

Contrasting the SeqN task to its reference revealed the cerebral areas involved in numerosity processing of sequentially presented non symbolic material. A right-lateralized hemispheric activation was identified in the inferior parietal lobule around the IPS. Areas of activation were also observed in the right inferior frontal gyrus, the right supplementary motor area, and the left insula (Table 9.1b and Figure 9.3A). Only a small extra activation focus (k=1) appeared in the left superior parietal lobule at an uncorrected threshold (p<.003). Contrasted to SimN, the SeqN task activated a large focus in the right inferior frontal gyrus. Areas of activation were also observed in the right supplementary motor area (SMA) and in the left middle frontal gyrus (Table 9.1d).

Table 9.1: Brain areas showing significant activation for (a) Simultaneous numerosity (SimN), (b) Sequential numerosity (SeqN) categorisations each compared to its own reference task (Ref), (c) SimN contrasted to SeqN and (d) inversely SeqN contrasted to SimN, and (e) conjunction of the two numerosity tasks (SeqN and SimN).

	Brain regions	*L / R*	*k*	*x*	*y*	*z*	*t-statistic*
a	**[SimN-Fix]-[RefSimN-Fix]**						
	IPS/Inferior Parietal Lobule	R	693	30	-56	50	6.61****
	Inferior Temporal Gyrus	R	507	48	-58	-10	9.72****
	Inferior Temporal Gyrus	L	95	-46	-66	-10	6.33****
	Precentral Gyrus	R	74	48	10	32	5.81****
	Superior Parietal Lobule	L	219	-28	-58	64	3.95***
	Inferior Parietal Lobule	L	93	-46	-38	50	3.71***
b	**[SeqN-Fix]-[RefSeqN-Fix]**						
	Inferior Frontal Operculum	R	2462	56	16	22	8.31****
	Supplementary Motor Area	R	672	8	20	54	8.43****
	IPS/Inferior Parietal Lobule	R	532	44	-46	50	7.75****
	Inferior Frontal Gyrus	R	448	42	22	4	7.61****
	Insula	L	136	-32	24	0	6.59****
	Superior Parietal Lobule	L	1	-40	-52	68	2.89**
c	**[SimN-RefSimN]-[SeqN-RefSeqN]**						
	Middle Occipital Gyrus	L	371	-50	-70	32	5.98****
	Cingular Gyrus	L	234	-12	-40	38	5.99****
	Precuneus	L	100	-6	-64	72	5.68****
	Precuneus	R	82	6	-58	22	5.39****
d	**[SeqN-RefSeqN]-[SimN-RefSimN]**						
	Inferior Frontal Gyrus	R	1331	44	46	14	5.04****
	Supplementary Motor Area	R	326	8	20	58	4.97****
	Middle Frontal Gyrus	L	60	-42	46	16	3.64****
e	**[[SeqN-Fix]-[RefSeqN-Fix]] & [[SimN-Fix]-[RefSim-Fix]]**						
	IPS/Inferior Parietal Lobule	R	134	42	-46	48	6.20****
	Precentral Gyrus	R	74	48	10	32	5.81****
	Superior Parietal Lobule	L	2	-40	-52	68	2.72*

L = left hemisphere; R = right hemisphere; k = cluster size (number of voxels); x, y, z = stereotaxic coordinates of peak-height voxels; **** = *p*-values <.05 FWE corrected for multiple comparisons; *** = *p*-values <.001 uncorrected; ** = *p*-values <.003 uncorrected; * = *p*-values <.004 uncorrected.

3.2.3 Mode-independent numerosity processing

The conjunction of SeqN and SimN, each contrasted to its own reference, revealed the areas involved in numerosity processing regardless of the mode of presentation. Only two right hemispheric foci were found to be activated in common, one in the IPS (with a local maximum at

42 -46 48; Figure 9.3B) and one in the precentral gyrus (Table 9.1e and Figure 9.3A). A small left superior parietal activation (k=2) also appeared at an uncorrected threshold (p<.004).

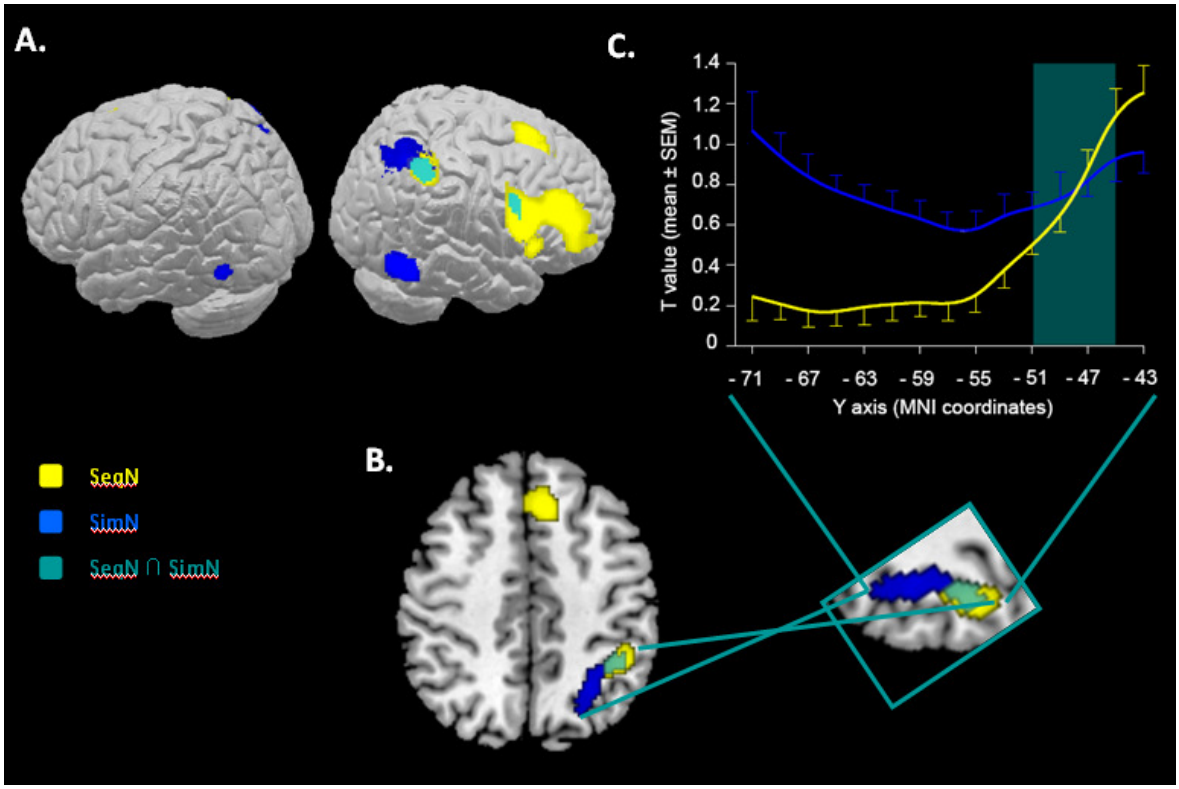

Figure 9.3: **(A)** Brain regions activated specifically and jointly in the two experimental tasks (i.e., SimN and SeqN). **(B)** The overlay of colors shows the extent of the ROI in the right IPS (maximum y = -41; minimum y = -71). Within this ROI, an anterior-to-posterior index was calculated by averaging the contrast-weighted t values (experimental *minus* reference tasks) along the medial-to-lateral (x axis) and superior-to-inferior (z axis) dimensions, within the range of -40 to -71 on the y axis in stereotactic space. The results of this analysis are plotted in the panel for SeqN and SimN tasks respectively. Error bars represent the standard error of the mean for contrast-weighted t values, averaged along the x and z axes.

In the voxel-by-voxel correlation analysis, the two right foci activated in the conjunction (i.e., IPS and precentral gyrus), one frontal area activated only in SeqN and a bilateral temporal inferior focus activated in SimN task were chosen as ROIs. The pattern of activation for sequential and simultaneous numerosity processing was significantly correlated across voxels in the two conjunction ROIs (right IPS: r= .5353, t_{14}=7.696, p<.001; right precentral gyrus: r=.4587, t_{14}=7.313, p<.001) and slightly correlated in the frontal gyrus (r=.174, t_{14}=2.188, p<.05). Conversely, correlations in the left and right temporal gyri were not significant (left temporal: r= .0533,

t_{14}=0.7, p>.4; right temporal: r= .1827, t_{14}= 2.028, p>.05). Direct comparisons between ROIs correlations using paired *t*-tests showed significant differences between the right IPS and the right temporal gyrus or the right frontal gyrus (respectively, t_{14}=3.064, p<.01; t_{14}=3.482, p<.005), and also between the right precentral gyrus and the right temporal gyrus or the right frontal gyrus (respectively, t_{14}= 4.653, p<.001; t_{14}=2.872, p<.02), indicating that the positive correlations observed in the right IPS and in the right precentral gyrus are not an artifact.

Finally, the averaged *t*-values along the anterior-to-posterior axis for sequential and simultaneous numerosity were not significantly different for coordinates between -45 and -49 on *y* axis (all *p*-values >.05).

4. Discussion

The parietal cortices have been shown to underlie a notation- and modality-independent representation of numerical quantity (Dehaene et al., 1998; Piazza et al., 2006; 2007). Most studies investigating visual non symbolic numerosity processing used simultaneous material; few used sequential material. Therefore, although neurons that respond to numerosity irrespective of the presentation mode have been identified in monkeys (Nieder et al., 2006), whether or not the two modes of presenting numerosity dissociate or overlap totally or partially in humans has not yet been directly assessed. In the present fMRI study, participants were asked to categorize the numerosity of linear arrays of dots (simultaneous mode of presentation) or of sequences of flashed dots (sequential mode of presentation).

For the simultaneously presented numerosity categorization task, our results showed a bilateral involvement of parietal and frontal areas, predominantly in the right hemisphere. Bilateral activation of the IPS has been reported consistently in fMRI studies in numerosity comparison tasks (Ansari & Dhital, 2006) and in adaptation paradigms (Cantlon et al., 2006; Piazza et al., 2004; 2007). We recently observed a similar fronto-parietal network of activation using the same material but in a different task (comparison of two linear arrays of dots; Dormal & Pesenti,

2009), which ensures that the IPS is involved in core aspects of numerosity processing, whatever the task. The parietal cluster activated specifically by simultaneous numerosity included the posterior part of the IPS and corresponded to the human homologue of lateral intraparietal (LIP) as previously reported (Koyama et al., 2004; Sereno, Pitzalis & Martinez, 2001; Simon et al., 2002). By contrasting directly the two experimental tasks, a set of left posterior parietal areas was activated during the SimN task, most probably reflecting visual complexity and visuo-spatial processing of stimuli extending in space (Corbetta, 1998; Grill-Spector et al., 1999).

Most interestingly, sequentially presented numerosity processing was found to activate the right IPS in the present study. A strictly right-lateralized activation of parietal regions including the IPS was reported previously when participants had to explicitly compare sequentially presented temporal stimuli, using visual (sequences of squares) or auditory (sequences of tones) modalities (Piazza et al., 2006; Table 9.2). This right lateralized activity in response to sequentially presented material may reflect involvement of a system that allows the serial position of each item in a sequence to be followed. Such a mechanism was shown to be recruited by the enumeration of sequentially in contrast to simultaneously presented numerosities (Leroux et al., 2006; Nieder et al., 2006; Piazza et al., 2006), and might correspond to the accumulator stage postulated in computational models of number processing (Meck & Church, 1983; Nieder et al., 2006; Verguts & Fias, 2004). In line with this latter assumption, although the accumulation of relevant information preferentially involved LIP neurons in monkeys (Mazurek, Roitman, Ditterich & Shadlen, 2003; Roitman & Shadlen, 2002; Roitman et al., 2007), it has been observed in the right IPS in humans (Belin et al., 2002; Coull & Frith, 1998; Coull, Walsh, Frith & Nobre, 2003). The right inferior frontal gyrus was found more activated with sequential than simultaneous presentation, a result often reported in time measurement tasks (for a review, see Lewis & Miall, 2003a) and specifically when participants had to orient their attention during a certain period of time (Coull et al., 2003).

Table 9.2: Peak voxels of IPS activation in earlier fMRI studies investigating non symbolic numerosity estimation processing and Euclidian distances between our common IPS right activation and right parietal foci observed in numerosity fMRI studies.

Reference	Task	Range of numerosities	Modality	Mode	Coordinates of maxima						Euclidian distance from our right IPS activation site (in mm)
					Left IPS			Right IPS			
					X	Y	Z	X	Y	Z	
Piazza et al. (2004)	Hab	8-64	V	Sim	-36	-60	52	28	-56	52	17.66
Cantlon et al. (2006)	Hab	8-64	V	Sim	-31	-66	62	43	-47	69	21.05
Piazza et al. (2007)	Hab	20-50	V	Sim	-32	-57	46	46	-42	47	5.74
Piazza et al. (2006)	Comp	15	V/A	Seq	n.s.			52	-48	50	10.39
Ansari and Dhital (2006)	Comp	1-9	V	Sim	-32	-50	44	32	-49	46	10.63
Castelli et al. (2006)	Comp	5-15	V	Seq/Sim	-24	-48	48	33	-57	51	14.53
Dormal and Pesenti (in press)	Comp	5-9	V	Sim	-32	-52	52	46	-38	50	9.17
Mean					-31	-56	51	40	-48	52	12.74
S.D.					4	7	6	9	7	8	5.29
Our conjunction IPS Focus	Categ	6-8	V	Seq/Sim	n.s.			42	-46	48	

b= Habituation paradigm; Comp= Comparison task; Categ= Categorization task; V=Visual ; A=Auditive ; Sim= Simultaneous presentation ; Seq=Sequential presentation; x, y, z = reotaxic coordinates of peak-height voxels.

The conjunction of the two categorization tasks showed that the central part of the right IPS was activated by both simultaneous and sequential stimuli, and it may thus correspond to the anatomical locus of a mode-independent numerosity representation. It is worth noting that using simultaneous and sequential material allowed us to isolate a core numerical representation independent of spatial or temporal processing. Comparable results were indirectly suggested in Castelli et al.'s (2006) study in which the IPS was activated more when comparing discrete numerosities than continuous quantities, both in time and in space. According to computational models of numerosity representations (Dehaene & Changeux, 1993; Verguts & Fias, 2004), these mode-independent activations could underlie the number-selective coding step localized in the VIP in monkeys (Nieder & Miller, 2004) and in the anterior part of the IPS in humans (Cantlon et al., 2006; Piazza et al., 2004; 2007). The neural code in VIP responding to auditory as well as to visual numerosity seemed to be implicated either for sequential or simultaneous presented numerosity. As can be seen in Figure 9.3B, such an anterior-to-posterior gradient of activation

along the IPS observed in our results is consistent with electrophysiological data (Nieder et al., 2006) and with a recent proposition of neuroanatomical implementation of numerosity processing pathway (Santens et al., 2010). Indeed, the existence of a mode-independent numerosity representation is also supported by a neuronal recording study in which monkeys compared sequential and simultaneous numerosities (Nieder et al., 2006). Distinct populations of neurons inside the IPS were engaged in temporal and in spatial enumeration processes, and in a final convergence step, irrespective of whether stimuli were presented sequentially or simultaneously. In the present study, the right IPS activation observed in both categorization tasks may correspond to the human homologous area of this specific neuronal population in monkeys.

However, because of the limited spatial resolution of fMRI compared to the invasive electrophysiological methods used in monkeys, and the fact that coactivation of cerebral areas does not necessarily imply a common neural code but may simply be due to the activation of distinct intermingled neural populations (Cohen Kadosh et al., 2005; Pinel et al., 2004), these data must be interpreted with caution. The multi-voxel correlation analysis clarified whether the overlapping activations were due to inter-individual averaging and smoothing or to a true functional relationship. A high correlation was observed at the best available resolution between sequential and simultaneous tasks in the right IPS and the right precentral gyrus. Only a weak correlation was observed for the frontal gyrus, whereas no correlation was observed in bilateral temporal areas. These results support the idea of a functionally relevant role of these areas in numerosity processing, independent of the presentation mode. Finally, as proposed in a recent fMRI study (Santens et al., 2010), the posterior part of the IPS, corresponding to the number sensitive coding system (i.e., tuned in proportion of the number of elements), could be active as an intermediate code in the extraction of the information from the sensory stimulus, and project the information to the anterior part of the IPS, corresponding to the number selective coding system (i.e., tuned to a preferred numerosity), in the hierarchical processing of numerosity

information. Here, we extend this proposal by showing a different spatial distribution of the number sensitive IPS activations as a function of the mode of presentation: whereas simultaneous numerosity processing involved a more extended dorsal and posterior part of the IPS (between -51 and -71 in the Y coordinates axis), sequential presentation activated a more anterior part (between -41 and -43 in the Y coordinates axis).

In contrast to previous studies suggesting that parietal regions of both hemispheres implement a non symbolic numerosity representation (Cantlon et al., 2006; Piazza et al., 2004; 2007), a predominantly right parietal activation was observed in the present study in both numerosity categorization tasks, only small left parietal foci being observed at an uncorrected threshold in the SimN task. All right parietal activations reported in previous studies were spatially close to the present peak (mean Euclidean distance = 12.7 ± 5.29mm; Table 9.2) and were all situated along the IPS (Figure 9.4). The present results support a right hemispheric dominance for non symbolic numerosity processing, as suggested in neuropsychological studies reporting deficits in dot estimation more frequently after right than after left parietal damage (Warrington & James, 1967), whereas preserved non symbolic numerosity abilities but impaired symbolic number processing were observed in a patient with a left parietal lesion (Polk et al., 2001). The superiority of the right hemisphere in non symbolic numerosity estimation was also demonstrated in healthy individuals in tachistoscopic dot enumeration tasks (Kimura, 1966; McGlone & Davidson, 1973; Young & Bion, 1979). Indeed, when children (from 3 years old) and adults were asked to quantify a collection of dots presented briefly in their left or right visual hemifield, an overall left visual hemifield superiority was observed both for accuracy and response latencies. However, TMS impaired dot comparison after left but not after right IPS stimulation (Cappelletti et al., 2007; Dormal et al., 2008). How can these TMS results be reconciled with the present findings? The reason for the apparent discrepancy may be the greater variability in right IPS activation foci. Figure 9.4 shows the left and right IPS foci observed

in studies that specifically investigated the estimation of non symbolic numerosity, displayed on a standard template. The left IPS foci appear much closer to each other than the right IPS foci (see also Table 9.2). Given this greater right-sided variability, the probability that TMS was actually applied to the critical area at an individual level may be smaller for the right than for the left IPS, hence little or no overall effect of TMS after right IPS stimulation.

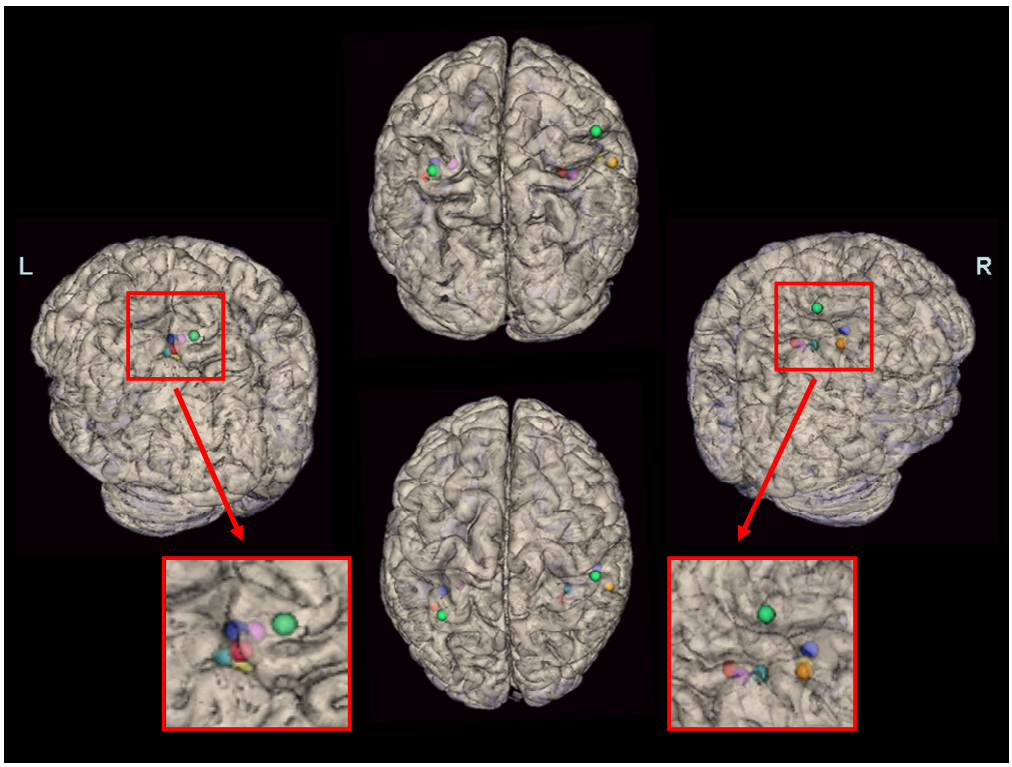

Figure 9.4: Non symbolic numerosity-related activation in the left and right parietal lobe. The activation foci reported in Table 8.3 are represented on a glass brain reconstructed from the T2-weighted images of the MNI template. Color code – Red: Piazza et al. 2004; Green: Cantlon et al. 2006; Yellow: Piazza et al. 2007; Orange: Piazza et al. 2006; Blue (Light): Ansari & Dhital 2006; Purple: Castelli et al. 2006; Blue (dark): Dormal & Pesenti, 2009.

Finally, although probably not specific to numerosity processing, the frontal activations observed bilaterally in both tasks likely reflect attentional control, as already suggested in previous studies on quantifying dots in the same range of numerosities (Sathian et al., 1999). Frontal activation may also be linked to the fact that there was a greater demand on working memory in the experimental tasks compared to reference tasks. Indeed, participants may have encoded each simultaneous or sequential numerosity, maintained this information active in

working memory, and then compared it with the stored “few” and “many” standard. It is plausible that the working memory load in the color reference tasks was lighter. This difference in cognitive recruitment was observed in the behavioral results: experimental tasks were more time consuming and more prone to error than their reference tasks. Assumption regarding which frontal focus of activation would be associated with stronger reliance on working memory are consistent with studies showing dorsolateral and ventrolateral frontal activation during the retention period in several visual memory tasks (for a review, Smith & Jonides, 1999). In line with this, one may object that task complexity also contributed to the pattern of IPS activation we observed as this activation has previously shown some modulation as a function of task difficulty (Göbel et al., 2004). However, the fact that very similar IPS activations are observed in the absence of an explicit task during passive numerosity changes (Ansari et al., 2006) suggests that response-selection requirements and task difficulty cannot be the only sources of IPS activation. This, in turn, makes the possibility that task complexity contributed to the pattern of results we observed in the IPS little plausible.

In conclusion, our results reveal, for the first time, that the right IPS and the right precentral gyrus are activated by the estimation of non symbolic numerosities whatever their mode of presentation. The functional relevance of the overlapping activation, demonstrated by the correlation analysis, thus supports the existence of a mode-independent non symbolic numerosity representation system in the human parietal cortex and in the precentral gyrus.

Chapitre 10

Discussion Générale

1. Questions expérimentales

L'objectif premier de ce travail résidait dans l'exploration des interactions fonctionnelles et neuroanatomiques existant entre le traitement de différentes magnitudes. Les résultats obtenus au cours des recherches antérieures ayant investigué ces relations présentant un certain nombre de limites et ne permettant pas d'aboutir à des conclusions fermes, une exploration étendue et systématique des interactions entre les dimensions numérique non symbolique, temporelle et spatiale a été entreprise, enrichie par la combinaison de plusieurs techniques d'investigation comportementales et neuroanatomiques et l'utilisation de stimuli soigneusement contrôlés.

L'ensemble des études présentées dans ce travail a tenté d'apporter des réponses à trois questions centrales, réponses visant à étendre les recherches existantes et à combler les manquements persistants quant aux relations directes présentes entre les magnitudes. Ces questions peuvent se résumer comme suit:

(1) Lorsque l'on est confronté à plusieurs dimensions simultanément, dans quelle mesure celles-ci vont-elles interagir ? Existe-t-il des interactions fonctionnelles réciproques entre les processus d'estimation de magnitude ?

(2) Existe-t-il un réseau cérébral spécifique et commun sous-tendant les processus d'estimation de la numérosité, de la durée et de la longueur ? Et si oui, quel est-il ?

(3) Les zones intrapariétales connues pour être impliquées dans le traitement numérique symbolique jouent-elles un rôle critique dans l'estimation de la numérosité ? En outre, ces aires cérébrales sont-elles également impliquées de façon nécessaire dans d'autres types de traitement (i.e., estimation de durée ou de longueur) ?

2. Synthèse des résultats

2.1 Première question: Interactions fonctionnelles entre les processus d'estimation de magnitude

Une première approche possible afin de déterminer l'existence d'une représentation commune sous-tendant les traitements de différentes magnitudes réside dans l'exploration de la présence d'interactions fonctionnelles entre plusieurs dimensions quantifiables. L'objectif des expériences présentées au cours des chapitres 2, 5 et 8 était donc d'investiguer, au moyen d'un paradigme expérimental de type Stroop, les effets de facilitation et d'interférence pouvant exister entre les dimensions numérique, temporelle et spatiale. L'étude décrite dans le chapitre 2 s'est tout d'abord intéressée aux interactions pouvant exister entre les dimensions numériques et temporelles. Les participants devaient comparer soit la numérosité soit la durée de séquences visuelles de points flashés rapidement pour lesquelles la numérosité et la durée étaient manipulées de façon indépendante afin de créer des paires congruentes, incongruentes ou neutres. Les résultats de cette étude indiquent que les indices numériques interférent avec le jugement de durée, alors que les indices temporels n'influencent pas le jugement relatif à la numérosité, suggérant un traitement plus automatique de la numérosité comparativement à la durée.

Dans un second temps, et en suivant une logique expérimentale semblable, les interactions entre le traitement de la numérosité et de la longueur ont été investiguées (chapitre 5). La tâche des participants était ici de comparer la numérosité ou la longueur de deux rangées linéaires de points, présentées de façon simultanée. Il s'est avéré que les indices spatiaux interféraient fortement avec le traitement de la numérosité tandis que l'interférence des indices numériques sur le traitement de la longueur n'était que modérée. Mises ensemble, ces deux études suggèrent l'existence de différences en terme d'automaticité entre ces différents processus de traitement, reflétant un continuum allant du plus au moins automatique.

Afin d'investiguer davantage cette proposition de continuum, une expérience utilisant le même paradigme Stroop, en combinant cette fois les trois dimensions simultanément, a été réalisée (chapitre 8). Les participants devaient comparer la numérosité, la longueur ou la durée de séquences de points présentés rapidement les uns après les autres de gauche à droite sur une ligne horizontale. Les trois dimensions étaient manipulées indépendamment au sein des trois tâches afin d'investiguer d'éventuels effets de facilitation et d'interférence entre les dimensions temporelle, spatiale et numérique, ainsi que la présence éventuelle d'interactions entre ces dimensions. Les résultats ont confirmé l'interférence des indices numériques sur le traitement des durées et, inversement, l'absence d'interférence des indices temporels sur le traitement des numérosités (chapitre 2); ils ont confirmé également l'interférence réciproque entre les indices spatiaux et numériques (chapitre 5). En outre, pour la première fois dans ce type de paradigme expérimental, l'interférence des indices spatiaux sur le traitement des durées ainsi que l'absence d'interférence des indices temporels sur le traitement des longueurs ont été démontrées. Enfin, un effet conjoint des indices numériques et spatiaux sur le jugement de durée a été mis en évidence.

2.2 Deuxième question: Substrats anatomiques des processus d'estimation de magnitude

L'exploration du substrat cérébral sous-tendant les processus cognitifs d'estimation de magnitude constituait l'objet central des chapitres 3, 6 et 9, basés sur la technique de l'IRMf. Comme cela a été décrit dans la partie introductive, les études antérieures utilisant cette technique pour explorer les corrélats cérébraux de l'estimation se sont intéressées principalement au traitement d'une seule dimension à la fois, démontrant à travers des paradigmes simples généralement de type soustractif[25], les zones cérébrales impliquées respectivement lors d'estimation de numérosités, de durées ou de longueurs. Si ces études semblent pointer unanimement le cortex pariétal, l'objectif de nos recherches était d'investiguer

[25] Soustraction entre les activités observées lors de la tâche expérimentale et une autre condition, généralement la tâche contrôle.

les zones communément activées par les différents processus d'estimation de magnitude au sein d'un même paradigme. L'étude présentée dans le chapitre 3 a tout d'abord permis d'identifier les aires cérébrales impliquées dans la comparaison de numérosité et de durée. Alors que les participants devaient catégoriser des séries de points flashés ou un point unique en fonction respectivement de la numérosité ou de la durée de ceux-ci, une analyse de conjonction a mis en évidence un large réseau fronto-pariétal latéralisé exclusivement à droite activé communément par ces deux processus. Dans une perspective d'implémentation fonctionnelle du modèle de Meck & Church (1983), le SIP droit pourrait sous-tendre le système de représentation de la magnitude généralisée, correspondant probablement aux étapes d'encodage et d'accumulation de ce modèle, alors que les zones frontales seraient quant à elles plutôt impliquées dans des processus plus tardifs de stockage en mémoire de travail et de prise de décision. L'étape d'accumulation pourrait correspondre à un des stades intermédiaires décrits dans le modèle computationnel du traitement de la numérosité (Verguts & Fias, 2004). La conversion des entrées visuelles vers le système de codage sélectif aux numérosités nécessite en effet le passage par deux étapes intermédiaires, une première étape de création d'une carte de localisation des éléments et enfin, une étape d'accumulation des éléments détectés. Cette dernière étape serait sous-tendue par la partie latérale du SIP chez le singe (Roitman et al., 2007) et par la partie postérieure du cortex pariétal supérieur chez l'être humain (Santens et al., 2010)[26].

Une seconde étude a exploré les zones cérébrales sous-tendant les processus de comparaison de numérosité et de longueur (chapitre 6). Les participants réalisaient des comparaisons de la numérosité de deux rangées de points alignés (Numérosité), de la longueur totale de ces mêmes séries de points (Longueur discrète) et de la longueur de deux rectangles noirs continus (Longueur continue). Les résultats d'activation ont montré l'implication bilatérale

[26] Toutefois, ces deux études ayant utilisé exclusivement des collections de points comprises entre 1 et 5 et présentées de façon visuelle et simultanée, l'activation de cette zone pourrait être dépendante du mode de présentation et/ou de l'étendue utilisés.

des régions pariétales, le long du SIP, dans le traitement explicite et implicite[27] de la numérosité et l'implication d'un réseau occipitopariétal latéralisé à droite dans le traitement de la longueur. Les analyses de conjonction ont mis en évidence l'activation commune lors des tâches de comparaison de longueur et de numérosité du SIP droit et du gyrus précentral droit. En excluant le traitement spatial automatique et intrinsèque des séries linéaires, il a été démontré que le SIP gauche était impliqué uniquement dans le traitement de la numérosité, alors que le SIP droit sous-tendait un mécanisme ou une représentation commune aux magnitudes spatiales et numériques.

Enfin, dans le chapitre 9, une dernière étude en IRMf s'est intéressée à la mise en évidence de zones cérébrales dépendantes et/ou indépendantes du mode de présentation de la numérosité, à savoir une présentation à travers le temps (i.e., séquentielle) ou à travers l'espace (i.e., simultanée). Les participants devaient réaliser des tâches de catégorisation basées sur la numérosité d'une rangée de points alignés ou sur la numérosité d'une séquence de points flashés. Une implication bilatérale des régions pariétales le long du SIP a été observée lors du traitement des numérosités présentées simultanément, alors que des activations uniquement latéralisées à droite étaient présentes pour le traitement des numérosités présentées séquentiellement. L'analyse de conjonction entre ces deux tâches a mis en évidence deux foyers d'activation dans l'hémisphère droit: le SIP et le gyrus précentral. Des analyses complémentaires plus précises ont permis d'établir l'existence, au sein du SIP droit, de sous-régions fonctionnellement différentes, réparties selon un axe antéro-postérieur et codant respectivement les numérosités présentées de façon séquentielle uniquement, séquentielle et simultanée, ou simultanée uniquement, démontrant ainsi pour la première fois chez l'être humain la présence conjointe de

[27] Le traitement explicite correspond aux activations observées lors de la tâche de comparaison de numérosité, tandis que les activations liées au traitement implicite sont mesurées lors de l'analyse de la tâche de comparaison de longueur discrète, masquée par les activations liées à la tâche de comparaison de longueur continue, mettant ainsi en évidence les zones responsables du traitement non-volontaire et automatique de la numérosité.

représentations numériques non symboliques dépendante et indépendante du mode de présentation.

2.3 Troisième question: Rôle causal des régions pariétales dans les processus d'estimation de magnitude

Si les études présentées dans les chapitres 3, 6 et 9 ont clairement mis en évidence une implication du cortex pariétal dans les différents traitements de magnitude, le rôle causal de ces régions dans les processus d'estimation de numérosité, de durée et de longueur ne peut être conclu à partir de ces résultats. Ce rôle causal a été investigué au moyen de deux études utilisant la SMT. Au cours de la première étude (chapitre 4), les participants devaient réaliser une tâche de comparaison soit de la numérosité de deux séries successives de points flashés rapidement, soit de la durée de deux points successifs. Après avoir réalisé ces deux tâches, les participants recevaient un train de stimulation à une fréquence de 1Hz pendant une durée d'environ 15 minutes. Immédiatement après la période de stimulation, les participants réalisaient à nouveau les deux mêmes tâches. Trois sites de stimulation ont été choisis chez chaque participant: le SIP gauche et droit, et le vertex comme site contrôle. Il est important de noter que les sites pariétaux ont été déterminés en référence aux coordonnées moyennes d'activation rapportées dans plusieurs études (e.g., Piazza et al., 2006) lors de tâches de comparaison de numérosités. Par rapport au site contrôle, les performances des participants étaient ralenties uniquement lors de la tâche de comparaison de numérosité après stimulation du SIP gauche. La tâche de comparaison de durée n'a été perturbée par aucune des stimulations pariétales. De plus, une interaction entre la distance et les sites de stimulation indique que cette perturbation de la tâche de numérosité n'a lieu que pour les items présentant une petite distance, soit les items nécessitant un traitement plus précis. Si l'activation de cette région intrapariétale a été démontrée préalablement par des études en neuroimagerie (e.g., Piazza et al., 2003; Castelli et al., 2006), les résultats de cette étude en SMT s'accordent avec l'idée que le SIP est impliqué de manière

causale dans le traitement de la numérosité. Toutefois, cette première étude suggère que seul le SIP gauche est nécessaire à l'intégrité du traitement comparatif de la numérosité, alors que le SIP droit n'est pas impliqué de façon critique dans ce processus. L'absence de perturbation dans la tâche de comparaison de durée après stimulation pariétale gauche et droite, semble indiquer que cette région n'est pas cruciale pour le traitement de la durée. Dès lors, s'il existe un substrat cérébral commun pour traiter les deux types de magnitude, cette région ne correspond pas à la zone du SIP spécifiquement mise en évidence lors de la comparaison de numérosités.

Utilisant une technique de neuronavigation guidée par les résultats préalablement obtenus chez ces mêmes participants dans une étude en IRMf et reconnue comme étant la technique prenant le mieux en considération la variabilité anatomique et fonctionnelle inter-individuelle (Sack et al., 2009), la seconde étude en SMT (chapitre 7) a mis en évidence l'implication cruciale et nécessaire du SIP droit tant dans le traitement de la numérosité que de la longueur. L'ensemble des participants avait donc préalablement participé à une de nos études en IRMf (soit celle du chapitre 6, soit celle du chapitre 9). Ces études avaient toutes deux révélé des foyers d'activation au niveau du SIP gauche et droit au cours d'une tâche d'estimation de numérosité. La localisation des sites de stimulation a ainsi été réalisée en fonction des coordonnées individuelles des pics d'activation durant cette tâche. Dans cette étude en SMT, les participants devaient réaliser une tâche de catégorisation de numérosités et de longueurs alors qu'un train de stimulations répétées était appliqué dès le début de la présentation de chaque stimulus à une fréquence de 10Hz. Par rapport au site contrôle, les performances des participants étaient altérées (i.e., augmentation significative du taux d'erreurs) après la stimulation du SIP droit et ce, quelle que soit la tâche[28]. D'une part, ces résultats étendent à l'hémisphère droit le rôle critique du SIP dans le traitement de numérosité, contrairement aux études précédentes

[28] Une différence marginale est toutefois observée entre les pourcentages d'erreurs observés lors de la stimulation du SIP gauche et du site contrôle, suggérant une possible implication du SIP gauche dans les jugements de numérosités et de longueurs.

limitant le rôle prépondérant du SIP à l'hémisphère gauche (Cappelletti et al., 2007; chapitre 4[29]). En outre, cette région du cortex pariétal est également impliquée de façon nécessaire dans les processus d'estimation de longueurs, suggérant la présence d'une représentation ou d'un mécanisme commun pour les magnitudes spatiales et numériques au sein du SIP droit.

3. Implications théoriques

3.1 Données comportementales

Dans un contexte de présentation visuelle séquentielle et pour l'étendue de numérosités, de durées et de longueurs utilisées dans nos expériences, les résultats de nos études comportementales utilisant un paradigme de type Stroop suggèrent l'existence d'un continuum d'automaticité au sein duquel le traitement de la numérosité prendrait place de façon la plus automatique, suivi par le traitement de la longueur, tandis que le traitement de la durée serait le traitement le moins automatique et par conséquent le moins interférent (Figure 10.1). Ce gradient d'automaticité pourrait par ailleurs être déterminé ou tout du moins influencé par la fréquence d'exposition et le degré d'expertise développé vis-à-vis de ces différentes dimensions de magnitude (Cohen et al., 1990). Par exemple, la comparaison explicite de durées, et plus précisément d'intervalles de quelques centaines de millisecondes, étant un comportement relativement plus rare dans la vie quotidienne que celui de l'estimation de numérosités, inférieures à dix, ou que la comparaison de longueurs de l'ordre de quelques centimètres, ceci pourrait rendre compte de l'absence d'effet interférent de la part de la dimension temporelle. Il est important de considérer ces résultats comme totalement dépendants de notre cadre expérimental, contraint par le type de tâches mais aussi l'étendue, les modalités sensorielles et le mode de présentation du matériel utilisé. Une illustration de cette dépendance par rapport au contexte expérimental se retrouve dans les différences observées entre les résultats obtenus dans

[29] Des pistes explicatives rendant compte des résultats récoltés dans nos deux études en SMT, concernant l'implication cruciale gauche ou droite des SIP dans le traitement de la numérosité et en apparence contradictoires, seront développées au cours du point 3.2.1.

notre seconde (chapitre 5) et troisième études Stroop (chapitre 8). Si une interférence réciproque entre les indices numériques et spatiaux est observée dans nos deux études, une influence plus forte des indices spatiaux par rapport à l'influence des indices numériques est présente lorsque le jugement a lieu sur des stimuli distribués spatialement et présentés de façon simultanée, alors que l'inverse (i.e., une influence plus marquée des indices numériques par rapport à l'influence des indices spatiaux) se retrouve lors de la comparaison de stimuli apparaissant de manière séquentielle[30]. Dès lors, de futures expériences avec une étendue plus large de magnitudes, du matériel et des tâches différentes s'avèrent nécessaire afin d'éventuellement pouvoir généraliser cette proposition de continuum.

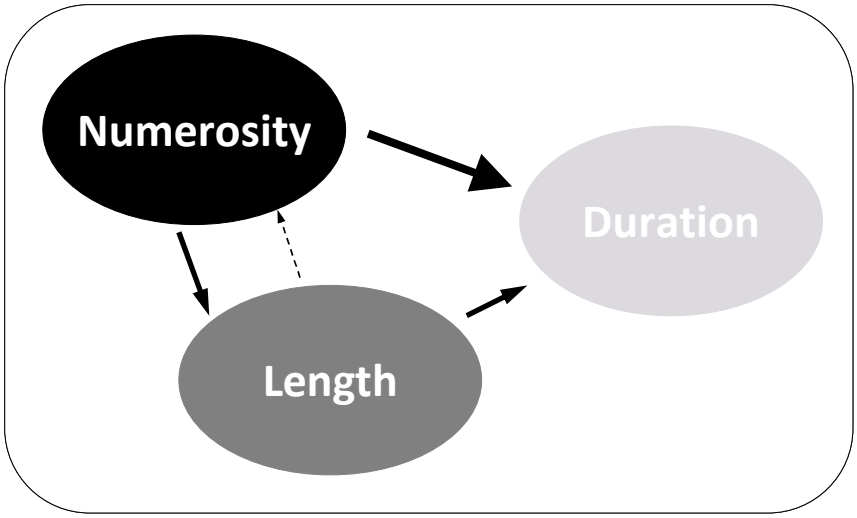

Figure 10.1: Proposition de continuum d'automaticité entre les dimensions de numérosité, de longueur et de durée, allant du plus au moins automatique, lors de la comparaison de matériel présenté de façon séquentielle.

Les conditions neutres des différentes tâches, correspondant aux lignes de base, ne différant significativement pas entre elles tant au niveau des latences de réponse qu'au niveau du taux d'erreurs, les différents profils d'interférence observés entre les dimensions ne reflètent pas une différence en termes de vitesse de traitement et ne peuvent être attribuées à des différences de sollicitation attentionnelle ou de degré de difficulté. Par ailleurs, si la présence d'interférence

[30] Notons qu'une absence d'interférence des indices de surface cumulée sur le jugement de numérosité a été observée dans une expérience utilisant également du matériel séquentiel (Barth, 2008).

unilatérale et non-symétrique permet de rejeter l'idée d'une représentation unique et exclusivement partagée de la magnitude, l'ensemble des résultats n'autorise toutefois pas de trancher entre l'existence de représentations totalement séparées ou partiellement partagées. Les paradigmes expérimentaux utilisés ne permettant pas de déterminer à quel stade du traitement a lieu l'interférence entre les dimensions, celle-ci pourrait prendre place au cours d'une étape plus tardive comme la prise de décision et ne pas impliquer l'activation d'une représentation commune, hypothétiquement responsable des effets d'interaction. Comme cela a été largement développé concernant l'effet Stroop classique (e.g., Atkinson, Drysdale & Fulham, 2003) ou encore l'effet de congruité de taille (e.g., Schwarz & Heinze, 1998), de futures études utilisant la technique des potentiels évoqués (PE) permettront d'investiguer le décours temporel précis de ces effets d'interférence et de facilitation. Contrairement à l'IRMf, cette technique offre une résolution temporelle importante et va permettre d'investiguer le moment exact où a lieu le conflit.

Dans ce type de paradigme interférent, deux modèles principaux d'interaction ont été proposés dans la littérature: le modèle d'interaction précoce et celui d'interaction tardive. Dans le premier modèle, les dimensions pertinente et non-pertinente sont traitées dans un premier temps en parallèle et convergent vers une représentation analogue commune au niveau de l'étape de comparaison, où le conflit prend place (Moyer & Landauer, 1967; Figure 10.2A). Le second modèle postule quant à lui l'occurrence d'une interaction à un stade plus tardif du processus, à savoir durant l'initiation de la réponse (e.g., lors de la sélection de la réponse, de la préparation motrice ou de l'exécution de la réponse; Schwarz & Heinze, 1998). Selon cette proposition, les dimensions pertinente et non-pertinente sont traitées en parallèle lors de l'étape de comparaison, le conflit se produisant uniquement lors d'une des étapes de réponse (Figure 10.2B).

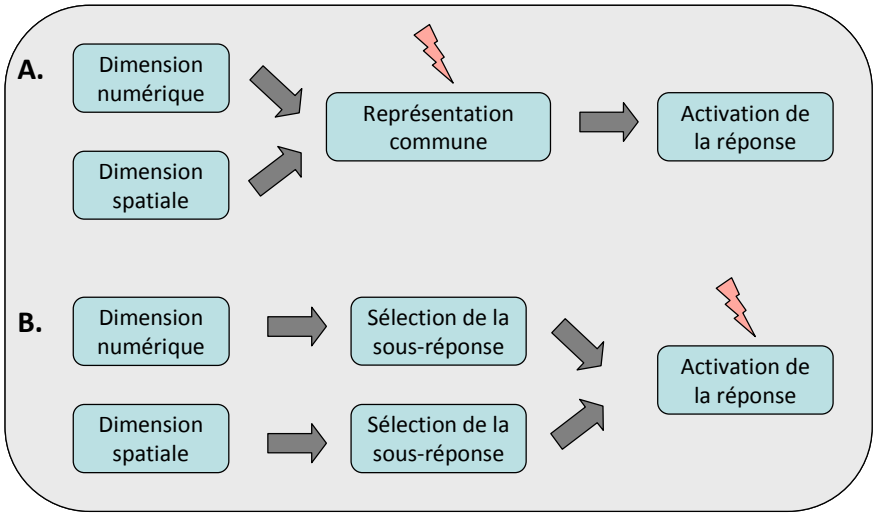

Figure 10.2: Représentation schématique du modèle d'interaction (A) précoce et (B) tardive, dans le cadre du paradigme de congruité de taille (adapté de Schwarz & Heinze, 1998).

Alors que le premier de ces modèles suggère l'existence d'une représentation commune, le second modèle n'implique quant à lui pas de passage vers ce type de représentation, chaque traitement ayant lieu en parallèle. Déterminer, au moyen de la technique des PE, le décours temporel des interactions entre les dimensions de numérosité et de durée d'une part, et des dimensions de numérosité et de longueur d'autre part, permettra de préciser l'étape de traitement où a lieu le conflit entre les dimensions et d'apporter des informations sur l'existence ou non d'une représentation commune de la magnitude.

3.2 Données neuroanatomiques

3.2.1 Processus d'estimation de la numérosité

Une partie des implications de nos données portent sur les substrats cérébraux sous-tendant les processus de traitement de la numérosité. Au départ de ce travail, une dizaine d'études avaient tenté d'explorer les bases cérébrales des processus d'estimation numérique non symbolique à travers divers paradigmes d'habituation (Ansari & Dhital, 2006; Cantlon et al., 2006; Piazza et al., 2004; 2007), des tâches de comparaison (Castelli et al., 2006; Piazza et al., 2006), d'énumération (Fink et al., 2001; Piazza et al., 2002; 2003; Sathian et al., 1999) ou encore

d'additions simples (Venkatraman et al., 2005). En utilisant principalement du matériel visuel présenté spatialement sous forme de collections aléatoires de points, l'ensemble de ces études a mis en évidence des activations bilatérales ou latéralisées à droite dans les régions pariétales le long du SIP. Nos résultats apportent tout d'abord une confirmation des données antérieures, révélant l'implication systématique du cortex pariétal au cours de l'estimation de numérosité.

De plus, grâce à la diversification des tâches (comparaison ou catégorisation) et du matériel (présentation séquentielle ou simultanée) utilisés, nos observations ont permis d'étendre les résultats précédents. En effet, une activation du cortex pariétal droit a été générée par l'estimation de la numérosité et ce, indépendamment du mode de présentation. Précédemment, les résultats d'une étude en IRMf avaient mis en évidence, de manière indirecte, des observations allant dans le même sens (Castelli et al., 2006). Cette étude avait pour objectif de comparer les activations cérébrales associées à la quantification de quantités discrètes (i.e., de numérosités) et de quantités continues. Ces quantités étaient représentées par des collections d'éléments verts et bleus changeant de manière abrupte ou progressive, dans le temps (présentation séquentielle de carrés verts et bleus) ou dans l'espace (présentation simultanées de rectangles bleus et verts). Les aires pariétales étaient davantage activées par la comparaison de numérosités discrètes que par la comparaison de quantités continues et ce, tant dans le temps que dans l'espace. Bien que l'objectif de cette étude ne résidait pas dans l'investigation de l'effet du mode de présentation des stimuli sur les régions cérébrales activées, les résultats suggéraient indirectement que les SIP étaient activés par l'estimation de numérosités, que celles-ci soient représentées par la succession d'éléments ou par leur présentation simultanée.

Par ailleurs, la mise en évidence dans nos recherches d'un foyer pariétal communément activé par l'estimation de numérosités indépendamment de leur mode de présentation est également consistante avec une étude réalisée au moyen de l'enregistrement cellulaire chez le singe au cours d'une tâche d'appariement de numérosités présentées soit simultanément soit

séquentiellement (Nieder et al., 2006). Dans cette étude, trois populations neuronales distinctes sensibles à la numérosité avaient été identifiées au sein du SIP. La première répondait sélectivement aux numérosités présentées séquentiellement, la seconde aux numérosités présentées simultanément et la troisième, distincte des deux premières, comprenait des neurones déchargeant uniquement au cours de la période de délai de rétention qui suit la présentation d'une numérosité, que celle-ci ait été présentée séquentiellement ou simultanément. Les neurones de cette troisième population neuronale auraient pour rôle d'encoder la quantité numérique perçue indépendamment de son mode de présentation. Ainsi, les voxels localisés dans le SIP de l'hémisphère droit communément activés par les deux tâches de catégorisation de numérosités dans nos études pourraient refléter l'activité de ces populations neuronales sensibles à la numérosité indépendamment du mode de présentation des stimuli. Une analyse plus fine de la distribution de l'activation au sein du SIP a par ailleurs démontré l'existence d'un gradient antéro-postérieur, démontrant une activation sélective pour un mode de présentation séquentiel au niveau antérieur ou simultané au niveau postérieur, et une activation commune pour les deux modes dans la partie centrale. Ces résultats chez l'être humain reflètent donc pour la première fois la correspondance fonctionnelle avec l'observation des trois populations distinctes chez le singe, et suggèrent la coexistence de représentations de la numérosité dépendantes et indépendantes du mode de présentation.

Comme proposé récemment dans une étude IRMf (Santens et al., 2010), cette distribution spatiale des activations au sein du SIP pourrait refléter les différentes étapes de codage proposées dans le modèle computationnel du traitement de la numérosité (Verguts & Fias, 2004). Ainsi, la partie postérieure du SIP correspondrait à l'étape de codage sensitif de la numérosité et projetterait ensuite les informations vers la partie antérieure du SIP (i.e., partie centrale de l'activation observée communément pour les deux modes de présentation) abritant l'étape finale de codage sélectif. Si ces auteurs délimitent l'étape de codage sensitif à la partie

postérieur du SIP uniquement dans le cadre de stimuli présentés simultanément, nos données étendent cette proposition en montrant une distribution spatiale de cette étape, différente en fonction du mode de présentation des numérosités: alors que du matériel simultané et distribué dans l'espace implique effectivement des régions postérieures du SIP, du matériel séquentiel distribué à travers le temps activeraient des régions plus antérieures.

En outre, nos données ont également souligné l'importance spécifique de l'hémisphère droit lors du traitement de matériel séquentiel (Figure 10.3). En effet, alors que des activations bilatérales du SIP sont révélées lorsque le jugement de numérosité s'effectue sur du matériel présenté à travers l'espace (i.e., séries linéaires de points; chapitres 6 et 9), seul le SIP droit montre une activation significative lors du traitement de numérosité présentée séquentiellement (i.e., séquence de points flashés rapidement; chapitres 3 et 9). Ces résultats sont en accord avec les deux seules études ayant utilisé du matériel séquentiel, rapportant soit une activation pariétale exclusivement observée dans l'hémisphère droit (Piazza et al., 2006), soit la présence d'un effet de difficulté décelé au niveau du SIP droit pour les numérosités spécifiquement affichées au cours du temps (Castelli et al., 2006). Cette activation latéralisée à droite, déjà observée au sein du SIP droit dans d'autres tâches non-numériques nécessitant le maintien d'informations sérielles (Belin et al., 2002; Coull & Frith, 1998; Coull et al., 2003), pourrait correspondre à l'étape d'accumulation postulée dans les modèles computationnels du traitement numérique (Meck & Church, 1983; Nieder et al., 2006; Verguts & Fias, 2004) comme mentionné ci-dessus.

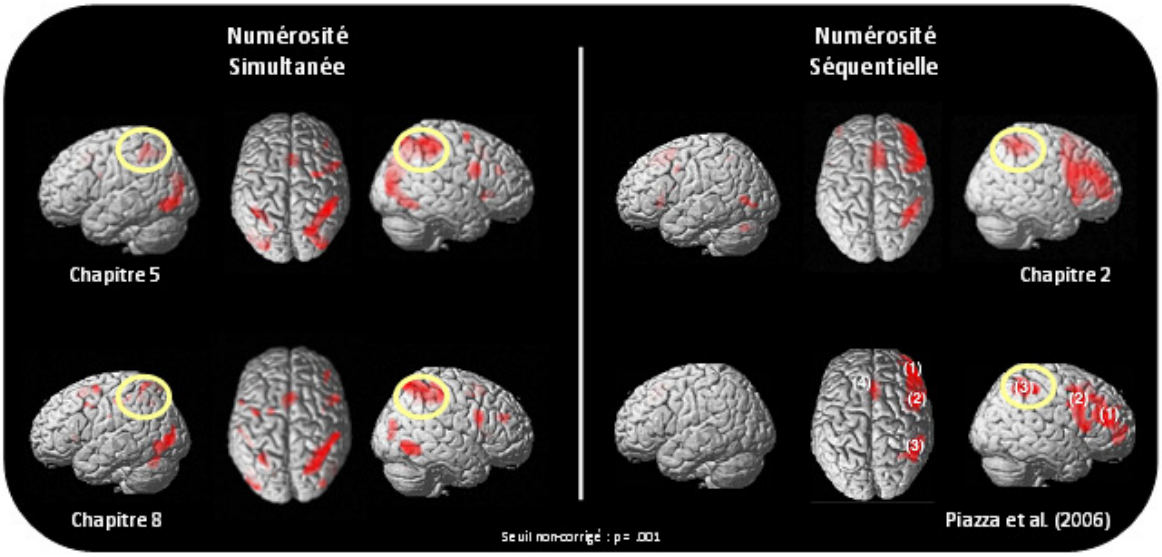

Figure 10.3: Synthèse des activations observées lors des tâches d'estimation de numérosités présentées de façon simultanée (gauche) dans les études présentées dans les chapitres 6 et 9 et de façon séquentielle (droite) lors de l'étude décrite dans le chapitre 3 et dans l'étude de Piazza et ses collaborateurs (2006). Une activation bilatérale des SIP est observée pour les numérosités simultanées, alors que seul le SIP droit est impliqué dans le traitement de numérosités séquentielles.

L'utilisation dans ce travail de la technique complémentaire de SMT pour explorer la contribution nécessaire et causale des zones pariétales activées dans les processus d'estimation de magnitudes a permis d'apporter des informations supplémentaires importantes, notamment sur les spécificités hémisphériques liées au mode de présentation de la numérosité. Ainsi, la contribution des SIP dans l'estimation de numérosités présentées dans l'espace de façon simultanée a été confirmée, une perturbation significative des performances numériques étant observée après stimulation du SIP droit, alors qu'un effet marginal est observé lors de la stimulation du SIP gauche (chapitre 7). Par contre, la domination hémisphérique droite rapportée dans nos études IRMf concernant le traitement de numérosités séquentielles n'a pas été retrouvée lors de la stimulation de cette zone. Au contraire, seule la stimulation du SIP gauche, a donné lieu à des performances déficitaires pour la tâche de comparaison numérique (chapitre 4). Il faut cependant noter qu'une interaction avec la distance a également été observée dans cette étude indiquant que la perturbation après stimulation gauche n'est observée que sur les items présentant une petite distance, autrement dit, les items les plus complexes. Or, le cortex pariétal

gauche semblerait jouer un rôle prépondérant dans les processus numériques précis, alors que son homologue droit serait davantage impliqué dans les traitements approximatifs (Chochon et al., 1999; Dehaene & Cohen, 1991; Piazza et al., 2006). Chaque hémisphère pourrait par ailleurs abriter des représentations et/ou des processus de traitement numériques qualitativement différents. En effet, si au départ, chaque hémisphère serait doté d'un système de traitement des magnitudes dépendant du ratio, disponible précocement et partagé avec les autres espèces animales, au cours de l'apprentissage et avec le développement de l'utilisation des nombres verbaux et des doigts dans le comptage pour représenter les numérosités, un affinement progressif de la représentation au sein de l'hémisphère dominant pour le langage et les habiletés manuelles serait observé (Andres et al., 2005; Piazza et al., 2004; 2007). Cette trajectoire développementale des apprentissages numériques aboutirait à la spécialisation hémisphérique observée chez l'adulte: le SIP gauche serait à même de réaliser les traitements numériques précis sollicités dans les tâches de discrimination de numérosité par exemple, alors que son homologue droit sous-tendrait le système basique dépendant du ratio et moins précis, particulièrement efficace pour réaliser des tâches de catégorisation de numérosité. Les SIP gauche et droit abriteraient dès lors chacun des représentations distinctes et complémentaires capables de traiter la numérosité de façon spécifique. De plus, on notera que la technique de neuronavigation basée sur les données IRM de chaque participant utilisée lors de cette étude ne permet de tenir compte que de la variabilité anatomique interindividuelle et néglige dès lors la variabilité fonctionnelle, importante particulièrement dans le cortex pariétal (Cohen Kadosh et al., 2007). Enfin, une propagation de l'effet de la SMT à travers les connexions interhémisphériques et les relais thalamiques ne peut être écartée (Driver et al., 2009). Si c'est quelques pistes explicatives pourraient rendre compte des divergences observées entre les résultats de nos deux expériences en SMT, de futures études combinant SMT et IRMf apparaissent donc comme nécessaires pour clarifier les rôles spécifiques des SIP gauche et droit dans le traitement de numérosité.

3.2.2 Processus d'estimation de la magnitude

Une des implications majeures de ce travail réside dans la mise en évidence d'un foyer pariétal latéralisé dans l'hémisphère droit activé communément par l'estimation de numérosité, de durée et de longueur et observé pour la première fois de façon directe entre ces trois dimensions non symboliques. En effet, l'investigation des zones cérébrales communes entre les processus d'estimation de numérosité et de durée d'une part (chapitre 3), et entre les processus d'estimation de numérosité et de longueur d'autre part (chapitre 6), a permis de démontrer l'implication d'une zone pariétale droite, situé le long de la partie horizontale du SIP. Bien que ces résultats soient issus de deux études séparées, ayant testés deux groupes de volontaires différents et utilisant des paradigmes expérimentaux distincts, c'est un foyer pariétal commun quasi identique[31] qui a été mis en évidence à travers nos deux études (Figure 10.4). Ce foyer d'activation commun pourrait dès lors constituer le corrélat neuroanatomique d'un mécanisme ou d'un système de représentation de la magnitude généralisée (Walsh, 2003).

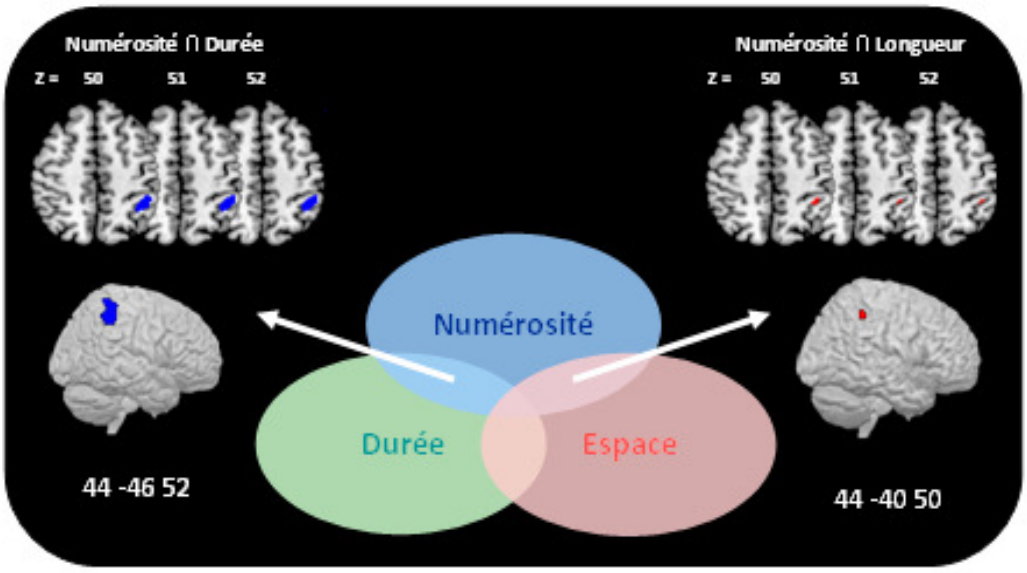

Figure 10.4: Foyer d'activation commun situé au niveau du SIP droit pour les processus d'estimation de la numérosité et de la durée (gauche) et de la numérosité et de la longueur (droite). Coupes axiales et reconstruction en trois dimensions à partir d'un cerveau standard.

[31] Distance euclidienne observée entre les deux pics d'activation observés dans les analyses de conjonction entre la tâche de numérosité et de durée d'une part et de numérosité et de longueur d'autre part et situés dans le SIP droit: 6.32 mm (Figure 10.4).

Le cortex pariétal, région cérébrale de convergence sensorielle, semble être le candidat idéal pour le rôle de "cortex primaire de la magnitude" (Bueti & Walsh, 2009; Walsh, 2003). Cette zone abrite en effet dès la naissance un système analogue dédié à l'action et capable d'effectuer des traitements généraux dichotomiques liés aux quantités de type "Plus que - Moins que", "Plus rapide - Plus lent", "Plus proche - Plus lointain", "Plus grand - Plus petit", système sur lequel pourrait venir au cours du développement se greffer les habiletés de discrétisation numérique. En outre, avec le rôle prépondérant du cortex pariétal dans les transformations sensori-motrices liées à l'action, il semble naturel que les données spatiales et temporelles, reconnues comme essentielles dans la métrique de l'action, partagent des zones cérébrales proches de cette zone pariétale. Toutefois, comme souligné par Walsh (2003), si le cortex pariétal constitue une zone centrale, il ne constitue pas le seul et unique foyer responsable des processus de traitement de la magnitude. Ainsi, par exemple, l'implication du cortex préfrontal dans différents traitements de magnitude mise en évidence au cours de récentes études tant chez le singe (Diester & Nieder, 2008; Nieder & Miller, 2003; Tudusciuc & Nieder, 2009) que chez l'être humain (e.g., Lewis & Miall, 2008b; Rao et al., 2001; Rusconi, Bueti, Walsh & Butterworth, in press) a également été conjointement observée lors de l'estimation de numérosité et de durée dans notre recherche (chapitre 3). Si les données neurophysiologiques chez le singe semblent indiquer une activité différente et plus précoce du cortex pariétal par rapport à l'activité préfrontale (Nieder & Miller, 2003; Tudusciuc & Nieder, 2009), peu d'informations sont à l'heure actuelle disponibles quant à l'apport similaire ou distinct de ces zones durant les processus d'estimation de magnitude chez l'homme, les études se focalisant principalement sur le rôle du cortex pariétal jusqu'à présent. Lors d'études futures, les avancées méthodologiques récentes au niveau de l'analyse des données issues des études en IRMf, notamment dans le développement des analyses de connectivité (e.g., Dynamic Causal Modelling; Friston, Harrison & Penny, 2003; Granger Causal Modelling; Roebroeck, Formisano & Goebel, 2003; Structural Equation Modeling; Büchel & Friston, 1997)

constituent des pistes intéressantes afin d'éclaircir le rôle spécifique de chaque région au sein de ce réseau cérébral sous-tendant la représentation de la magnitude généralisée.

Il semble important de souligner une autre limite liée à la technique d'imagerie utilisée dans nos travaux. Etant donné la faible résolution spatiale de l'IRMf en comparaison aux techniques d'enregistrement neuronale chez l'animal, rien ne permet d'assurer que les zones activées communément au sein du SIP droit sous-tendent la représentation de la magnitude tant numérique, que temporelle ou spatiale par des populations neuronales identiques (Grill-Spector & Malach, 2001). En effet, des populations neuronales spécifiques à chaque dimension localisées dans des régions proches au sein du SIP pourraient être à l'origine du foyer pariétal communément activé par les différentes tâches au cours de nos études. La mise en évidence de populations neuronales distinctes chez le singe répondant de manière spécifique mais aussi de façon commune pour divers modes de présentation (i.e., présentation séquentielle *vs.* simultanée; Nieder et al., 2006) ou diverses dimensions (numérosité *vs.* longueur; Tudusciuc & Nieder, 2009), couplée aux résultats démontrant la présence de sous-régions impliquées soit de manière dépendante ou indépendante du mode de présentation des numérosités et organisées suivant un axe antéro-postérieur le long du SIP (chapitre 9), suggère la coexistence de représentations spécifiques et partagées de la magnitude au sein de cette région. Par ailleurs, les résultats de nos études en SMT semblent converger avec cette proposition. En effet, si le SIP droit (et peut-être le gauche) est impliqué de façon nécessaire tant dans le traitement de la numérosité que dans celui de la longueur, suggérant l'existence d'une représentation commune pour ces deux magnitudes, par contre, une dissociation est observée au sein du SIP gauche (pour la partie du sillon stimulée lors de cette étude) entre le traitement de la numérosité et de la durée (i.e., seules les performances dans la tâche de discrimination de numérosité étaient affectées par cette stimulation). Cette dissociation est en faveur de la présence de représentations spécifiques et concernées par une seule dimension. Il faut noter toutefois que dans ces deux études, quelle que soit la procédure de sélection des sites pariétaux de stimulation (i.e., soit sur base de données

moyennes d'activations observées dans la littérature, soit sur base de données fonctionnelles individuelles récoltées préalablement dans une étude IRMf), ces choix étaient réalisés en fonction des données d'activation recueillies dans des tâches liées au traitement de la numérosité uniquement. L'objectif premier de nos études en SMT était en effet de déterminer dans quelle mesure les zones pariétales impliquées de façon nécessaire dans le traitement de la numérosité l'étaient également dans d'autres traitements de magnitude. Ces choix ont pu ainsi avoir une influence sur le profil de résultats observé, et d'autres études à partir de données activées communément dans le traitement de plusieurs dimensions pourraient donner lieu à des résultats différents. Enfin, de façon intéressante, les résultats obtenus au cours d'une récente étude de cas (Cappelletti et al., 2009) semblent également aller dans le même sens, en postulant l'existence d'une représentation et/ou d'un mécanisme de traitement de la durée partiellement indépendants. Dans cette étude explorant les processus d'estimation de numérosité, de durée et de longueur, un patient présentant une lésion temporo-pariétale droite montrait des performances déficitaires lorsqu'il devait comparer des intervalles de temps, alors que ses capacités de comparaison de numérosité et de longueurs étaient totalement préservées. En plus de l'exploration individuelle du traitement de ces trois dimensions, les auteurs ont également investigué les effets d'interférence pouvant exister entre ces magnitudes grâce à divers paradigmes déjà utilisés dans d'autres études chez des participants sains. Ainsi, un effet d'interférence unilatérale de la durée sur le jugement numérique ainsi que des effets réciproques entre les nombres et l'espace ont été observés, témoignant d'un certain recouvrement entre les représentations de ces dimensions. Toutefois, étant donné la présence d'une dissociation au niveau des tâches basiques d'estimation, les auteurs ont postulé que ce recouvrement ne serait que partiel. De nouvelles études de cas sont nécessaires afin d'établir une double voire une triple dissociation et de pouvoir confirmer l'existence de représentations partiellement indépendantes au sein du SIP pour les trois types de dimensions de magnitude étudiées. De plus, globalement, des données supplémentaires d'imagerie récoltées chez l'être humain et appliquant par exemple

des paradigmes événementielles d'habituation ou des analyses de corrélations multivariées sont nécessaires pour aboutir à des conclusions fermes.

3.3 Liens entre les données comportementales et neuroanatomiques

Bien qu'investiguant des niveaux de traitement différents, de façon intéressante, des liens peuvent être établis entre nos résultats comportementaux et neuroanatomiques. D'une part, la présence d'effets d'interférence unidirectionnelle ou bidirectionnelle entre les différentes dimensions de magnitude s'accorde parfaitement avec l'existence de foyers d'activation se chevauchant partiellement ou totalement au sein du SIP droit et sous-tendant les processus d'estimation. Il a en effet été suggéré que si les différentes dimensions à traiter impliquaient des structures cérébrales similaires, une interférence comportementale entre ces informations de magnitude devrait prendre place (Fias et al., 2001). Alors qu'au niveau neuroanatomique, nos données rapportent la présence de zones d'activation communes au sein du SIP droit que ce soit entre les tâches d'estimation de numérosité et de durée d'une part ou de numérosité et de longueur d'autre part, au niveau comportemental, des effets d'interférence sont effectivement observés lors du traitement de stimuli pour lesquels ces diverses dimensions sont manipulées.

D'autre part, les résultats observés dans nos études en SMT semblent également concorder avec les effets d'interférence comportementaux rencontrés dans les études Stroop. Ainsi, alors qu'une perturbation des performances est observée après stimulation du SIP droit de façon similaire tant pour le traitement de la numérosité que pour celui de la longueur, des effets d'interférence réciproques entre ces deux dimensions sont présents au niveau comportemental, suggérant doublement l'existence de mécanismes et/ou de représentations communs aux processus de traitement numérique et spatial. Par contre, entre les dimensions de numérosité et de durée, seuls les indices numériques interfèrent avec le jugement de durée, les indices temporels n'ayant aucune influence sur le jugement de numérosité. Cette asymétrie se retrouve également dans les résultats de notre étude en SMT, où seule la comparaison numérique non

symbolique est affectée par la stimulation du SIP gauche, la tâche de durée n'étant perturbée par aucune des stimulations par rapport au site contrôle. Ces résultats démontrent l'intérêt de la combinaison des techniques comportementales et de neuroimagerie, chacune apportant des informations complémentaires.

4. Limites et perspectives

Au terme de ce travail, il semble opportun de souligner l'existence de deux limites principales, déjà abordées précédemment. Il s'agit d'une part des tâches et du matériel utilisés au cours de nos différentes études, limitant inévitablement la généralisation de nos résultats, et d'autre part, des techniques expérimentales et des méthodes d'analyses adoptées jusqu'à présent.

Dès le départ, certains choix ont du être réalisés quant au type et à l'étendue des stimuli pour les différentes dimensions de magnitude étudiées. Par souci d'équilibre expérimental et afin de permettre des comparaisons fiables entre nos résultats, ces dimensions ont généralement été maintenues constantes à travers nos différentes études. Dès lors, il apparaît clair que nos conclusions ne sont applicables qu'aux processus d'estimation de numérosités, de durées et de longueurs tels que nous les avons définis préalablement et que des recherches futures variant les paradigmes et les propriétés des stimuli et explorant des magnitudes plus étendues sont nécessaires afin de pouvoir généraliser nos résultats. De plus, les magnitudes ne se restreignant évidemment pas aux dimensions numériques, temporelles et spatiales, l'investigation d'autres processus d'estimation de dimensions quantifiables, comme l'estimation du poids, du volume ou encore de la taille, doit être envisagée dans de futurs travaux.

Par ailleurs, ce travail s'est fondé sur l'utilisation de trois types d'investigation majeurs. D'une part des études comportementales ont été effectuées afin d'explorer les relations fonctionnelles entre les différentes magnitudes et d'établir la présence d'interactions entre ces trois dimensions lors de tâches de comparaison. D'autre part, afin de mettre en évidence le

substrat cérébral sous-tendant de façon commune les processus d'estimation de ces magnitudes, des études en neuroimagerie fonctionnelle ont été réalisées. Enfin, la technique de SMT a été utilisée de façon complémentaire aux études IRMf afin de déterminer le rôle causal des régions pariétales activées dans les processus d'estimation de magnitude. Si la combinaison de ces diverses techniques s'est avérée efficace en vue de répondre aux questions inhérentes à ce travail et a donc permis d'enrichir les connaissances relatives au traitement des magnitudes, chacune de ces techniques présentent cependant certaines limites, suggérant la nécessité d'envisager d'autres moyens d'investigation ou tout du moins de diversifier les paradigmes et méthodes d'analyses dans les études futures. Ainsi, par exemple, la technique de l'IRMf, si elle présente une bonne résolution spatiale, est au contraire associée à une résolution temporelle faible. L'utilisation de techniques neurophysiologiques comme les potentiels évoqués, présentant quant à elles une forte résolution temporelle, est donc essentielle dans le futur pour explorer le décours temporel précis de ces différents traitements. En effet, déterminer le décours temporel de ces traitements permettra notamment de mettre en évidence le stade où prend place les interactions entre les différentes dimensions et d'apporter des informations sur le passage nécessaire ou non par une étape de représentation commune. Finalement, bien que la SMT permettent d'apporter des informations sur la spécificité de certaines régions dans des processus cognitifs définis, des études neuropsychologiques sur des patients cérébrolésés ou des groupes de patients présentant une pathologie spécifique constituent une voie d'investigation à privilégier afin d'établir l'existence possible d'associations ou de dissociations de déficits liés au traitement des différentes dimensions de magnitude. L'existence de telles dissociations permettra de confirmer de façon claire la présence de représentations partiellement indépendantes et spécifiques pour chaque dimension de magnitude.

En conclusion, l'ensemble de ce travail a permis de souligner l'importance des processus d'estimation de numérosité, de durée et de longueur, présents de façon précoce chez le jeune enfant et partagés par d'autres espèces animales.

A un niveau comportemental, quelques effets classiques (e.g., distance, taille) sont partagés par ces trois processus, démontrant par ailleurs des trajectoires développementales similaires. L'exploration des interactions existant entre ces différentes dimensions, à travers des paradigmes interférents de type Stroop et en veillant à contrôler de façon soignée le matériel utilisé, a mis en évidence l'existence d'un continuum d'automaticité au sein duquel le traitement de la numérosité prendrait place de façon la plus automatique, suivi par le traitement de la longueur et enfin celui de la durée. L'investigation future du décours temporel de ces effets de facilitation et d'interférence, grâce par exemple à la technique des PE, permettra d'identifier l'étape lors de laquelle le conflit entre les dimensions prend place et d'établir si un passage vers une représentation commune est nécessaire ou non.

A un niveau neuroanatomique, nos études convergent vers l'implication commune, dans les différents processus d'estimation de magnitude explorés, d'une région cérébrale située le long du SIP droit. Ce foyer d'activation commun sous-tend dès lors un mécanisme et/ou un système de représentation de la magnitude généralisée, comme postulé par Walsh (2003). L'existence de cette représentation commune permet d'une part de rendre compte des divers effets comportementaux d'interférence observés entre les dimensions de magnitude, et d'autre part, des perturbations observées tant dans le traitement de la numérosité que dans celui de la longueur après la stimulation du SIP dans notre étude en SMT. Toutefois, si une représentation commune existe, le SIP semble également abriter des représentations partiellement distinctes. En effet, les résultats de plusieurs domaines d'investigation semblent aller dans ce sens. Ainsi, tant les données d'enregistrement neuronal chez le singe, que l'étude des processus d'estimation chez un patient cérébro-lésé, indiquent l'existence conjointe de représentations communes et distinctes. De même, la présence de certaines interactions unilatérales entre les dimensions de magnitude dans nos études comportementales, la perturbation unique du traitement de la numérosité après stimulation du SIP gauche alors qu'aucun effet n'était observé sur le jugement

de durée, ou encore l'exploration plus précise de la distribution des activations le long du SIP, appuient favorablement cette proposition. La combinaison de futures études tant comportementales, neuropsychologiques, neurophysiologiques ou en neuroimagerie, permettra d'établir le rôle exact de ces différentes représentations pariétales et de faire la lumière sur l'éventuelle implication d'autres régions cérébrales pouvant ainsi constituer un véritable système de représentation de la magnitude.

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