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ASSESSMENT OF IMPULSIVITY: THE INNOVATIVE APPROACH OF VIRTUAL REALITY

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Cette thèse est rédigée en anglais tel qu'il est permis dans les règlements des études de cycles supérieurs (136) de l'Université du Québec à Trois-Rivières. Dans ce cas, le règlement interne mentionne l'obligation de présenter un exposé substantiel rédigé en langue française dans lequel sont présentés les objectifs, la méthodologie et les résultats obtenus; une discussion sur l'ensemble des articles publiés ou rédigés pour publication et du travail réalisé.

Ce document est rédigé sous la forme d'articles scientifiques, tel qu'il est stipulé dans les règlements des études de cycles supérieurs (Article 138) de l'Université du Québec à Trois-Rivières. Les articles ont été rédigés selon les normes de publication de revues reconnues et approuvées par le Comité d'études de cycles supérieurs en psychologie. Le nom du directeur de recherche pourrait donc apparaitre comme coauteur de l'article soumis pour publication.

Abstract

The assessment of impulsivity is a central task for neuropsychologists. This can be a puzzling challenge as all currently available instruments have drawbacks. Although impulsivity is a multidimensional construct, common tasks do not permit assessment of multiple components of impulsivity, at least not simultaneously. There are also doubts concerning the predictive values of the results obtained on such tasks, that is, their ecological validity. Virtual reality (VR) is emerging as a versatile and reliable tool to assess cognitive functions, including inhibition and impulsivity. It is thought to address the shortcomings of traditional assessments by providing the patient situations that are similar to his daily life. Predictive validity is therefore increased. This thesis aimed at studying the contribution of VR to impulsivity assessment. To do so, a virtual reality task capable of assessing multiple components of impulsivity simultaneously was developed. The first chapter contains the introduction. In Chapter 2, a review paper describing impulsivity, its different conceptualizations, and available tasks to assess it is presented. In Chapters 3 and 4, two experiments and their results are described. This thesis suggests that VR represents a robust and valid new alternative to assess impulsivity in adolescents and adults. Furthermore, the ClinicaVR: Stroop is a valid option to evaluate multiple components of impulsivity concurrently. These results suggest that VR is superior to other current existing methods. Findings from this thesis show that VR allows evaluating impulsivity shortly and reliably with adolescents or adults. These results will help both clinicians and researchers to better understand impulsivity and improve its assessment.

Keywords: Impulsivity, inhibition, virtual reality, neuropsychological assessment, ClinicaVR: Classroom-Stroop, ClinicaVR: Apartment – Stroop, validity, reliability, norms, go no-go task.

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Science is simply the word we use to describe a method of organizing our curiosity
-Tim Minchin

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Résumé substantiel en français

L'évaluation de l'impulsivité est une tâche centrale en neuropsychologie. Peu d'instruments sont disponibles afin d'apprécier la complexité et la diversité des composantes qui forment ce construit. Les tâches disponibles se centrent généralement sur une composante de l'impulsivité. Il est pourtant reconnu depuis plusieurs années que l'impulsivité n'est pas un construit unidimensionnel (voir Evenden, 1999).

Les méthodes d'évaluation utilisées pour mesurer l'impulsivité sont également questionnées. Les questionnaires, autrefois populaires, sont maintenant déconseillés. Leur valeur prédictive semble en effet faible pour expliquer les comportements impulsifs dans la vie de tous les jours (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Drouin-Germain, Henry, Lalonde, Beauchamp, & Nolin, 2012; Henry, Jacob, Lacoursière-Girard, Nolin, & Joyal, 2013a). Plus précisément, les tâches neuropsychologiques en général (dites traditionnelles ou de type laboratoire) ont été développées pour décrire des profils cognitifs en regard à une valeur normative. Ces tâches réfèrent généralement à des tâches papier-crayon. Leur validité écologique, ou la prédiction des comportements en vie quotidienne, est donc moindre (Parsons, Carlew, & Sullivan, 2015).

La réalité virtuelle (RV) a le potentiel de pallier à plusieurs des limites des tâches traditionnelles. Cette technique permet de créer des conditions d'évaluation qui ne sont généralement pas accessibles à l'aide de tâches habituellement utilisées en

neuropsychologie (Gould et al., 2007; Makam et al., 2004; Matheis et al., 2007; Phelps, Fritchle, & Hoffman, 2004). La RV permet entre autre de simuler des situations de la vie quotidienne en y ajoutant des tâches cognitives calquées sur les tests traditionnels. Les propriétés psychométriques de ces tâches sont donc généralement conservées. De plus, toutes les actions du participant sont enregistrées et comptabilisées, ce qui permet des analyses plus poussées et récupérables. Ainsi, en plus d'apprécier la performance (bonne ou mauvaise réponse) à une tâche, les résultats permettent de mettre en lumière les processus associés à l'obtention du résultat. Les conditions d'évaluation de type laboratoire sont donc combinées à des situations qui sont proches de la vie quotidienne (Wilson, Foreman, & Stanton, 1997). La valeur écologique et la prédiction des comportements seraient donc meilleures avec les tâches virtuelles qu'avec les tâches traditionnelles en milieu expérimental (Armstrong et al., 2013; Henry et al., 2013a; Henry, Nolin, & Joyal, 2011; Nolin & Boucher, 2011; Nolin, Stipanicic, Henry, & Allain, 2013; Nolin, Stipanicic, Henry, Joyal, & Allain, 2012; Parsons, Courtney, Arizmendi, & Dawson, 2011; Parsons et al., 2015). En plus de la prédiction des comportements en vie réelle, la RV est un outil versatile qui permet des conditions d'évaluation ou d'intervention uniques. Ce thème sera abordé lors de la section sur la réalité virtuelle. Comme elle combine les propriétés psychométriques des tâches à un contrôle des variables présentées, cet outil semble prometteur pour l'évaluation de l'impulsivité.

Objectifs de la thèse

L'objectif principal de la présente thèse était d'étudier la contribution de la RV à l'évaluation de l'impulsivité. Pour ce faire, une tâche mesurant l'impulsivité en RV a été développée. Il était prédit que la RV aurait une valeur prédictive plus grande que les tests traditionnels d'impulsivité.

Pour répondre à l'objectif principal de cette thèse, trois articles sont proposés. Le premier article (Chapitre 2) vise à recenser systématiquement le concept d'impulsivité et à proposer une définition opérationnelle de ce construit. Les deux articles suivants (Chapitres 3 et 4) se concentrent sur le développement et la validation d'un outil novateur en RV pour mesurer l'impulsivité : le ClinicaVR: Stroop (VR-Stroop). Les trois articles de cette thèse seront décrits ci-après sous forme de résumé. Le contexte théorique, les méthodologies et les résultats seront brièvement abordés pour chacun d'entre eux. Ce résumé sera complété par une discussion générale qui reprendra les résultats en globalité.

Chapitre 2: Henry, M., Jacob, L., & Joyal, C. C. (2015). Évaluation clinique de l'impulsivité. *Revue Québécoise de Psychologie, 36*(2), 7-30.

L'impulsivité est une entité clinique multidimensionnelle complexe, fluctuante dans le temps et difficile à évaluer. Les instruments valides et accessibles, mesurant directement ses différentes composantes, sont relativement peu nombreux. De plus, les revues de la documentation concernant la mesure de l'impulsivité sont rares, et celles disponibles sont incomplètes (Matusiewicz & Lejuez, 2012; Parker & Bagby, 1997) ou centrées sur des logiciels vendus par leurs auteurs (Dougherty, Mathias, Marsh, & Jagar, 2005; Mathias, Marsh-Richard, & Dougherty, 2008). Le but de cet article était de faire une recension plus complète et objective des façons d'évaluer les différents types d'impulsivité. Une définition conceptuelle et opérationnelle de l'impulsivité, ainsi qu'une description exhaustive et critique des instruments de mesure disponibles pour évaluer chacun de ses aspects ont été proposées.

Tel que mentionné précédemment, l'impulsivité est une entité clinique complexe, multifactorielle et divisible en plusieurs sous-types (Evenden, 1999). Selon Moeller et collègues (2001), il s'agit d'« une prédisposition à réagir rapidement et sans planification à des stimuli internes ou externes, sans égard aux conséquences possibles pour l'individu impulsif ou les autres » [traduction libre] (p. 1784).

Plusieurs typologies peuvent être trouvées dans la littérature, mais celles-ci ne sont pas toutes compatibles. Les typologies les plus connues sont : l'état impulsif vs le trait impulsif (Eysenck & Eysenck, 1978; Moeller, Barratt, Dougherty, Schmitz, & Swann, 2001); l'impulsivité fonctionnelle vs dysfonctionnelle (Caci, Nadalet, Baylé, Robert, & Boyer, 2003; Dickman, 1990); l'impulsivité motrice, attentionnelle ou cognitive et la non-planifiée (Patton & Stanford, 1995); la trop grande spontanéité, l'absence de persévérance, et l'insouciance (Gerbing, Ahadi, & Patton, 1987); la précipitation, le défaut de préméditation, le manque de persévérance et la recherche de sensation

(Whiteside & Lynam, 2001); la trop grande vitesse d'exécution, la faible inhibition d'une réponse et la non considération des conséquences futures (Dougherty et al., 2009).

Ces composantes distinguent différents sous-types d'impulsivité que l'on peut regrouper de la façon suivante :

1) Impulsivité motrice (trop grande spontanéité, précipitation ou vitesse d'exécution exagérée);
2) Faible capacité d'arrêt (difficultés à empêcher l'exécution d'un geste déclenché);
3) Impulsivité attentionnelle, impulsivité cognitive ou manque de persévérance (déficit de l'attention; grande sensibilité à l'interférence interne ou externe, vigilance précaire);
4) Gratification immédiate (évitement des délais);
5) Recherche de sensations, prise de risques, insouciance et insensibilité pour les conséquences (je-m'en-foutisme et absence de planification).

Une description exhaustive et critique des instruments de mesure disponibles pour évaluer chacun de ces aspects a ensuite été présentée dans l'article. Les différentes tâches neuropsychologiques disponibles sur le marché ont été décrites en regard de leur composante d'appartenance.

Même si l'impulsivité est reconnue comme un construit qui n'est pas unitaire, plusieurs auteurs mesurent encore ce construit avec un seul test. Pourtant, une méta-analyse réalisée par van Mourik et ses collègues (2005) a conclu que les tâches traditionnelles démontrent des corrélations faibles avec les construits de l'impulsivité. Leur valeur prédictive est par contre augmentée lorsque plusieurs tâches évaluant les sous-types de l'impulsivité sont administrées (Perugini, Harvey, Lovejoy, Sandstrom, & Webb, 2000).

L'article conclu en proposant la RV comme une approche qui pourrait pallier aux limites énumérées. En effet, la RV pourrait permettre l'évaluation de plusieurs composantes de l'impulsivité de façon simultanée. Ce thème est la trame des deux prochains articles.

Chapitre 3: Henry, M., Joyal, C. C., & Nolin, P. (2012). Development and initial assessment of a new paradigm for assessing cognitive and motor inhibition: the bimodal virtual-reality Stroop. *Journal of Neuroscience Methods, 210*(2), 125-131.

Afin d'étudier l'apport de la RV à l'évaluation de l'impulsivité, une nouvelle tâche virtuelle a été validée dans le cadre de cette thèse. Le paradigme du Stroop a été utilisé comme base principale, puisqu'il s'agit de l'une des mesures les plus reconnues pour mesurer l'inhibition (Lezak, 2004; Lezak, Howieson, Bigler, & Tranel, 2012). Cette tâche a été adaptée et intégrée à un appartement virtuel par la firme Digital Media Works (DMW) sous le nom de ClinicaVR: Stroop (VR-Stroop). Dans cette représentation virtuelle de la vie quotidienne, l'individu est immergé dans un salon où se trouvent plusieurs objets distrayants (ex. : un téléphone cellulaire qui sonne).

Objectifs. Les objectifs de cet article étaient 1) de mesurer la validité interne; 2) de vérifier si un effet Stroop pouvait être provoqué avec la présentation de stimuli bimodaux; et 3) d'explorer si le VR-Stroop proposé dans cet article était en mesure d'évaluer plusieurs composantes de l'impulsivité.

Méthode. Cette étude a été conduite en deux phases. Dans un premier temps, une phase pilote a été mise en place afin d'évaluer les conditions optimales de l'expérimentation (objectif 1). Le confort de la salle d'évaluation, les consignes présentées ainsi que l'écart entre chacun des stimuli (l'intervalle inter-stimuli - ISI) ont été étudiés. Certaines coquilles informatiques ont également été résolues.

Dans un deuxième temps, le VR-Stroop et des tâches traditionnelles mesurant l'inhibition et l'impulsivité ont été administrés afin d'étudier la validité de la tâche virtuelle (objectifs 2 et 3).

Participants. L'échantillon total de cette étude était composé de 71 participants. Pour la phase pilote, 33 adultes ont été sélectionnés parmi l'entourage des évaluateurs. La moyenne d'âge était de 26,1 ans (écart-type de 9,2), 23 femmes pour 10 hommes. La deuxième phase (validation de la tâche) a été conduite auprès de 40 participants. Deux participants ont dû être retirés en lien avec des problèmes informatiques, dont une panne de courant. L'âge moyen de ce groupe était de 33,8 ans (écart-type de 15,2 ans).

Instruments. Tous les participants de l'étude ont été évalués avec les cinq instruments suivants. La présentation des instruments était contrebalancée pour tous les participants.

1) Le *Stroop traditionnel* (D-KEFS; (Delis, Kaplan, & Kramer, 2001). Le participant doit effectuer quatre tâches d'identification de stimuli. Seulement les conditions 1 et 3 de cette tâche ont été compilées. La première tâche consistait à nommer des rectangles imprimés selon des couleurs d'encre différentes (vert, rouge, bleu). La troisième tâche demandait au participant d'inhiber l'automatisme de lecture en nommant la couleur de l'encre dans laquelle des mots de couleurs (vert, rouge, bleu) ont été imprimés (vert, rouge ou bleu). Ainsi, si le mot vert était écrit avec une encre de couleur bleue, le participant devait dire "bleu". Le temps pour accomplir la tâche ainsi que le nombre d'erreurs ont été compilés. Cette tâche mesure le contrôle de l'interférence interne;
2) Le *Elevator Counting Task with Distractions* (TEA; (Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994) est une tâche de contrôle des interférences externes. Les participants doivent s'imaginer être dans un ascenseur dans lequel l'indicateur d'étages est défectueux. Afin de savoir à quel étage se situe l'ascenseur, le participant devait compter les sons graves comme un mouvement de l'ascenseur vers un étage inférieur et les sons aigus comme un mouvement vers un étage supérieur. La tâche comportait dix essais et le nombre de bonnes réponses était comptabilisé;

3) Le *Continuous Performance Task second edition* (CPT-II; (Conners, Epstein, Angold, & Klaric, 2003) est une tâche informatisée de 14 minutes qui évalue l'impulsivité motrice, l'attention soutenue et la vigilance (Lezak, 2004). Le participant devait cliquer le plus rapidement possible sur la souris lorsqu'une lettre apparaissait à l'écran, sauf lorsque la lettre était un "X". Les lettres étaient de couleur blanche et projetées sur un fond d'écran noir. Au total, 360 lettres (dont 36 "X") ont été présentées à des intervalles de 1, 2 ou 4 secondes. Dans le cadre de cette expérimentation, les temps de réaction, les erreurs de commissions, les omissions et les variabilités de réponses ont été prises en compte;
4) Le *Stop-it Task* (Verbruggen, Logan, & Stevens, 2008) est l'une des meilleures mesures d'inhibition (Nolan, D'Angelo, & Hoptman, 2011). Durant cette tâche, deux formes blanches sont présentées sur un fond d'écran noir. Lorsque la forme était un carré, le participant devait appuyer sur la touche de gauche. Si la forme était un cercle, la touche de droite doit être appuyée. Cette tâche, à la base simple, est accompagnée d'essais avec une composante "no-go" où une action doit être arrêtée. Ainsi, pour 25 % des essais, un bip sonore accompagne la présentation de la forme. Le participant devait alors ne rien faire. La particularité de cette tâche repose sur un algorithme qui évalue en temps réel le temps de réponse moyen de la personne. Lorsque la personne a une bonne réponse (c'est-à-dire qu'elle inhibe correctement le mouvement), le délai d'apparition du bip sonore augmente de 50 ms, ce qui rend l'inhibition de la réponse plus difficile au

prochain essai. Ce délai est réduit de 50 ms lors d'une mauvaise réponse. Pour cette tâche, le temps de réaction (*Stop-Signal Reaction Time* - SSRT) et le délai (*Stop-Signal Delay* - SSD) associé ont été considérés;

5) Le *VR-Stroop* comporte deux conditions. À l'aide d'un casque, le participant est plongé dans un environnement virtuel représentant un appartement. Le participant est assis au salon, face à une télévision. Lors de la première condition, des blocs de couleurs (rouge, bleu ou vert) sont présentés de façon aléatoire à l'écran du téléviseur. Au même moment, une couleur est nommée verbalement par l'entremise de haut-parleurs. La particularité de ce Stroop virtuel est qu'il repose sur une représentation bimodale des stimuli (audio et visuel). Le participant doit cliquer sur la souris lorsque la couleur nommée correspond à la couleur de l'encre affichée. Lorsque la couleur nommée ne correspond pas à la couleur de l'encre, le participant ne doit rien faire. Un total de 144 stimuli sont présentés lors de cette tâche, pour lesquels 72 sont des stimuli cibles. Cette condition a été développée pour mesurer les temps de réaction, l'attention sélective, et le contrôle de l'interférence externe.

La deuxième condition présente des mots (bleu, rouge ou vert) écrits avec la même couleur d'encre (le mot bleu écrit en bleu – essai congruent) ou avec une couleur d'encre différente (bleu écrit en vert – essai non congruent) au téléviseur. Au même moment, une couleur est nommée verbalement par l'entremise des haut-parleurs. Le mot entendu est nommé par la même voix que pour la condition 1 et les participants doivent cliquer lorsque le mot entendu est le même que la couleur de l'encre du mot écrit. Des 144 stimuli, 72 sont des stimuli-cibles, dont 36 sont des stimuli congruents et 36 sont des stimuli non congruents. En plus des variables mesurées lors de la condition 1, cette tâche a été développée afin de mesurer l'interférence cognitive (l'effet Stroop).

Questionnaires. Deux questionnaires ont été complétés par les participants suite à l'expérience virtuelle. Le premier était le questionnaire de l'Université du Québec en Outaouais portant sur les cybermalaises (Bouchard, Robillard, & Renaud, 2007). Ce questionnaire évalue la présence et l'intensité des symptômes pouvant être associés à une expérience virtuelle comme les maux de tête ou les étourdissements. Le deuxième questionnaire portait sur le sentiment de présence (Robillard, Bouchard, Renaud, & Cournoyer, 2002).

Résultats et brève discussion. Afin de répondre aux hypothèses du présent article, trois types d'analyse ont été choisis. Tout d'abord, une série de test-*t* pairés a été effectuée afin de choisir l'ISI qui convenait le mieux à la population générale. Les résultats ont démontré qu'un ISI de 2000 ms était associé à un effet plafond. Ainsi, la tâche était trop facile pour les participants. Ceux-ci obtenaient en moyenne, pour 72 bonnes réponses possibles, 71,6 bonnes réponses (écart-type : 0,7) pour la condition 1 et 69,9 bonnes réponses (écart-type 6,6) pour la condition 2. De plus, aucune différence significative n'a été observée entre les deux conditions. Un ISI de 1000 ms a donc été préconisé, car une meilleure distribution était observée.

Le deuxième objectif de cet article était de vérifier si un effet Stroop pouvait être provoqué avec le VR-Stroop. Pour ce faire, des analyses portant sur l'interférence interne créée par la nature des stimuli de la condition 2 ont été effectuées. La condition 2 comporte des essais congruents et non congruents. Si un effet d'interférence est présent, les essais non congruents devraient être associés à un temps de réaction plus long que les essais congruents (moins d'interférence, donc plus facile). Un temps de réaction moyen significativement plus élevé a été observé pour les essais non congruents (0.691s ± 0.099 vs 0.599s ± 0.054, t (1, 37) = -7.22, $p < .0001$), suggérant un effet d'interférence.

Le troisième objectif de cette expérimentation était de statuer sur les propriétés psychométriques du VR-Stroop. Des analyses corrélationnelles ont d'abord été effectuées entre le VR-Stroop et les autres tâches neuropsychologiques. Les résultats ont suggéré que le VR-Stroop est significativement associé à des tâches mesurant l'impulsivité. Plus précisément, la condition 1 est associée au CPT-II et à la tâche d'ascenseur, tandis que la condition 2 est associée au Stop-it, au Stroop traditionnel et à la tâche d'ascenseur. Des analyses supplémentaires de régression ont démontré que des variables provenant de la tâche d'ascenseur, le CPT-II, le Stop-it et le Stroop traditionnel étaient des prédicteurs significatifs des scores du VR-Stroop. Pour la condition 1, 27,6 % de la variance des temps de réaction pour les bonnes réponses était expliquée par ces variables, tandis que ce score était de 51,4 % pour la condition 2. Ces résultats suggèrent que le VR-Stroop comporte des composantes qui sont similaires aux composantes de l'impulsivité évaluées par ces tâches traditionnelles.

Enfin, les variables de sentiment de présence et de cybermalaises ont été étudiées afin de voir leurs impacts potentiels sur les performances au VR-Stroop. Il découle des analyses statistiques qu'un sentiment élevé de présence était associé à la tâche. De plus, le VR-Stroop était associé à un nombre et une intensité faible de cybermalaises.

Compte tenu des résultats encourageants de cet article, une expérimentation supplémentaire a permis d'appliquer la tâche du VR-Stroop auprès d'adolescents. Ceci est l'objet de la prochaine section.

Chapitre 4 : Lalonde, G., Henry, M., Drouin-Germain, A., Nolin, P., & Beauchamp, M. H. (2013). Assessment of executive function in adolescence: a comparison of traditional and virtual reality tools. *Journal of Neuroscience Methods, 219*(1), 76-82.

La présente section s'intéresse à une expérimentation supplémentaire où le VR-Stroop a été administré à des adolescents. Les principaux objectifs de cet article étaient 1) de comparer les performances obtenues au VR-Stroop à celles obtenues avec les tâches traditionnelles; 2) d'explorer la validité et les propriétés psychométriques de la tâche virtuelle; et 3) d'étudier la validité écologique du VR-Stroop.

Méthode.

Participants. Les participants de cette étude ont été recrutés sur une base volontaire par l'entremise de leur école secondaire. Au total, 38 adolescents (18 garçons et 20 filles) âgés entre 13 et 17 ans (moyenne d'âge : 14,69 ans) ont constitué l'échantillon.

Instruments. Tous les participants de la présente étude ont été évalués avec les tâches suivantes. Celles-ci ont été contrebalancées.

1) Le *Child Behavior Checklist* - CBCL (Achenbach & Rescorla, 2001). Ce questionnaire destiné aux parents mesurait les troubles internalisés et externalisés chez les adolescents (mentionnons par exemple l'anxiété, la dépression et les troubles d'attention);
2) Le *Behavior Rating Inventory of Executive Function* - BRIEF (Gioia, Isquith, Guy, & Kenworthy, 2000). Ce deuxième questionnaire complété par les parents mesurait les manifestations émotionnelles et comportementales des difficultés exécutives au quotidien;
3) Le *Wechsler Abbreviated Scale of Intelligence* - WASI (Woerner & Overstreet, 1999). Cette forme abrégée de la WISC-IV (*Weschler Intelligence Scale for Children*) a permis l'estimation d'un quotient intellectuel par l'entremise de deux sous-tests Matrices et Vocabulaire;
4) Le *Delis–Kaplan Executive Function System* - D–KEFS (Delis et al., 2001). Plusieurs tâches de cette batterie d'évaluation ont été utilisées afin d'évaluer les fonctions exécutives. Tout d'abord, le test de la Tour est une mesure de planification qui permet également de mesurer le temps d'initiation d'une réponse ainsi que le nombre de bris de règles (une mesure d'impulsivité). La tâche d'Interférence Mot-Couleur (Stroop traditionnel) permet quant-à-elle de mesurer l'inhibition cognitive. Le *Trail-Making Test* est une mesure de flexibilité mentale et de vitesse d'exécution où le participant doit relier des chiffres, des

lettres ou alterner entre un chiffre une lettre le plus rapidement possible. Le test de Fluence verbale est une tâche où l'adolescent doit nommer le plus de mots possibles compris dans une catégorie (sémantique, phonémique ou alternance entre deux catégories). Enfin, la tâche des 20 questions mesure le raisonnement abstrait. Le but de la tâche est de deviner, en posant le moins de questions possible, l'image choisie par l'évaluateur parmi 30 images possibles. L'évaluateur ne peut seulement répondre que par oui ou non aux questions posées;

5) Le *ClinicaVR: Classroom – Stroop* (Henry, Joyal, Drouin-Germain et al., 2012). La même tâche de Stroop utilisée dans l'article précédent a été présentée aux adolescents de cette expérimentation. Compte tenu de leur âge, la tâche a été placée dans une classe virtuelle comportant des objets distrayants associés à la vie scolaire (ex.: cloche qui sonne, éternuements d'un enfant dans la classe);

6) Le *Questionnaire de cybermalaises* (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993). Afin d'évaluer la nature et l'intensité des symptômes désagréables pouvant être associés à une expérience virtuelle, les adolescents ont complété ce questionnaire après leur expérience virtuelle.

Résultats et brève discussion. Afin de répondre au premier objectif, des analyses corrélationnelles ont été effectuées. Les commissions (impulsivité motrice) observées dans le VR-Stroop ont significativement été associées à la flexibilité cognitive et aux capacités d'inhibition. De plus, un temps de réaction plus court au VR-Stroop était associé à davantage de bris de règles dans le test de la Tour. Ces comportements sont compatibles avec une certaine impulsivité. Ainsi, le VR-Stroop est associé à des mesures traditionnelles d'impulsivité.

Afin de répondre au deuxième objectif, les performances au VR-Stroop ont été corrélées avec les résultats provenant des questionnaires. Des corrélations partielles entre le nombre de commissions au VR-Stroop et les résultats provenant des questionnaires ont également été étudiées. Les résultats provenant du questionnaire BRIEF démontrent que les adolescents ayant plus de commissions à la tâche virtuelle ont globalement des difficultés plus marquées à ce questionnaire mesurant les fonctions exécutives. Des résultats similaires ont été obtenus à l'aide du questionnaire CBCL. Un nombre élevé de commissions dans la tâche virtuelle était associé à des bris de règles ou des difficultés attentionnelles dans la vie quotidienne.

Enfin, le dernier objectif de cet article était de statuer sur la validité écologique du VR-Stroop. Des analyses de régression ont été utilisées afin de vérifier lequel du Stroop traditionnel ou virtuel était en mesure de prédire un plus grand pourcentage des résultats obtenus aux questionnaires. Le nombre de commissions lors de la condition 1 du VR-Stroop a permis d'expliquer une proportion significative de la variance des deux questionnaires. Plus précisément, pour le BRIEF, ces erreurs expliquent 46 % de l'échelle d'inhibition, 38 % de la régulation comportementale, 32 % de la métacognition et 37 % des fonctions exécutives en général. Pour le questionnaire du CBCL, les erreurs de commissions à la première condition du VR-Stroop ont expliqué 14 % des comportements de bris de règles et 41 % des difficultés attentionnelles. Les résultats provenant du Stroop traditionnel n'ont permis de prédire aucune des échelles ou sous-échelles de ces questionnaires. Ceci démontre donc la supériorité de la tâche virtuelle pour prédire un comportement par rapport à la tâche traditionnelle. Les composantes de l'impulsivité mesurées par la tâche virtuelle semblent donc évoquer des situations qui se produisent dans la vie quotidienne. Enfin, de façon comparable aux résultats obtenus lors de l'expérimentation précédente, le nombre et l'intensité des cybermalaises étaient faibles pour cette étude.

Les résultats découlant de cette expérimentation sont prometteurs pour le VR-Stroop qui semble mesurer plusieurs composantes de l'impulsivité de façon simultanée (inhibition, impulsivité motrice et cognitive). De plus, contrairement au Stroop traditionnel qui n'est pas associé à une prédiction des comportements observés, la valeur de prédiction du VR-Stroop est grande. La tâche virtuelle présente donc une bonne validité écologique.

Discussion

Les principaux objectifs de cette thèse étaient 1) d'explorer la conceptualisation de l'impulsivité en neuropsychologie afin de proposer une définition qui tiendrait compte de la complexité et de la diversité de ce construit; et 2) de proposer une approche novatrice pour évaluer l'impulsivité à l'aide de la RV.

Une définition complète de l'impulsivité englobant ses nombreuses composantes a été suggérée dans le cadre de cette thèse. Cette définition a ensuite permis de regrouper les tâches disponibles pour évaluer l'impulsivité en catégories afin de comparer leurs propriétés psychométriques. Une limite potentielle de la définition proposée dans cette thèse est qu'elle est basée sur un rationnel théorique plutôt que sur un rationnel biologique ou même neurologique. Des recherches futures en imagerie pourraient permettre d'infirmer ou non cette conceptualisation.

Afin de répondre au deuxième objectif, la tâche du VR-Stroop a été proposée. Cette tâche a été associée à plusieurs composantes de l'impulsivité tant chez les adolescents que les adultes. La tâche mesure donc des composantes d'inhibition cognitive, de temps de réaction, d'interférence externe (objets distrayants) et interne (effet Stroop). De plus, des analyses de régression ont démontré que le VR-Stroop est associé à des composantes d'impulsivité mesurées par les tâches traditionnelles.

Un autre avantage du VR-Stroop est sa validité écologique. Le VR-Stroop combine la rigueur des tâches psychométriques traditionnelles et la capacité de recréer des situations de la vie quotidienne. Alors que le Stroop traditionnel n'a pas été en mesure de prédire les comportements observés en milieu naturel, le VR-Stroop a été associé à un pourcentage non négligeable de prédiction des comportements en vie réelle tel que mesurés par les questionnaires CBCL et BRIEF. La supériorité écologique de la RV concorde avec ce qui est généralement observé dans la littérature.

La RV a été présentée dans cette thèse comme un outil versatile, relativement peu couteux, adapté au traitement psychologique (anonyme, non invasif, etc.) et permettant de repousser les limites de l'évaluation traditionnelle. Avec le développement constant des technologies, la RV deviendra certainement un outil encore plus accessible dans le futur, tant pour les chercheurs que pour les cliniciens. Les prochaines années révèleront probablement tout le potentiel de cette technique d'évaluation dans le champ de la neuropsychologie.

Chapter 1
Introduction

Humans are regarded as superior to other animals because they can mindfully control their behaviours. In general, humans can regulate themselves to achieve long-term goals, despite tempting distractions. This is possible when impulses or urges are controlled, and when actions are delayed or stopped (e.g. Barkley, 1997). When this cannot be achieved, the individual lacks inhibitory control and the action could be seen as impulsive (Conners & Staff, 2000; Logan & Cowan, 1984). Impulsivity, from the word impulse (in Latin *impulses)*, refers etymologically to something that is pushed, driven, incited or urged on (Kolb & Whishaw, 2009). The Merriam-Webster (2004) defines impulsivity as "doing things or tending to do things suddenly and without careful thought: acting or tending to act on impulse". However, as it will be exposed in this chapter, little consensus currently exists regarding the conceptualization or definition of impulsivity. The assessment of impulsivity also differs greatly from one task to another. Furthermore, the current available tasks fail to evaluate the same components of this construct.

As it will be seen in Chapter 2, options to assess impulsivity with psychological measures are limited, incomplete and not versatile. A technology is making progress in neurosciences as an adaptable and multipurpose tool: VR. With VR, parameters of the task can be chosen and the environment is tailored to the specific goals of the experiment or the examinee. VR is a computer-based technology that combines recent developments in portable technology with validated neuropsychological tasks. This thesis will suggest that VR assessment could overcome the limitations of current impulsivity assessments.

In the first section of this chapter, concepts of impulsivity are outlined. A definition of functional and dysfunctional impulsivity is provided. Trait impulsivity and state impulsivity are compared. The concept of inhibition, considered as the counter functions of impulsivity, is also defined. It will be concluded that impulsivity is not a unitary construct. In the second part of this introduction, the main components of VR as a novel approach to assess impulsivity in neuroscience are studied. A definition of VR is given and the various uses of VR in research and clinical settings are outlined. Then, the main components of the VR experience are presented as well as the equipment. The advantages of choosing VR are also provided. Lastly, third section of this introduction will present the objectives of the thesis.

Impulsivity: A complex construct

Impulsivity is the focus of many studies in neuropsychology, psychology and traditional cognitive experiments. Still, little consensus exists regarding its conceptualization (Buss & Plomin, 1975; Kipp, 2005; Moeller, Barratt, Dougherty, Schmitz, & Swann, 2001; Nigg, 2000; Whiteside & Lynam, 2001) or even its assessment (Barratt, 1985; Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Damasio, Tranel, & Damasio, 1997; Logan, 1994; Luria, 1966). Definitions of impulsivity are also abundant, as will be seen in the next section.

Definitions of impulsivity

Various definitions of impulsivity are found in the literature (e.g. Dougherty, Mathias, Marsh-Richard, Furr et al., 2009; Evenden, 1999; Moeller et al., 2001; Webster & Jackson, 1997). In psychiatry, a description of impulsive behaviours in five stages was proposed in the DSM-IV. Impulsivity was characterized by: 1) an impulse; 2) a growing tension; 3) a pleasure on acting; 4) relief from the act and, in some cases; and 5) guilt (APA, 2003). From a broader perspective, Evenden (1999) stressed that impulsivity is a complex and multifactorial construct divisible in many subtypes. This view is supported by others (Caswell, Morgan, & Duka, 2013; Cyders, Flory, Rainer, & Smith, 2009; Dougherty, Mathias, Marsh, & Jagar, 2005; Evenden, 1999; Whiteside & Lynam, 2001; Zuckerman, 1994). Impulsivity is generally considered as a tendency to act in a sudden, unpremeditated and spontaneous fashion. It is also sometimes defined as a disinhibition or poor inhibitory control (Lawrence, Luty, Bogdan, Sahakian, & Clark, 2009; Perales, Verdejo-García, Moya, Lozano, & Pérez-García, 2009). A widely accepted definition of impulsivity is provided by Moeller and colleagues: "a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others" (p. 1784, 2001). This definition includes the two concepts of « impulse » and « growing tension », outlined by the DSM-IV (APA, 2000). It also outlines impulsivity as a predisposition, indicating that it is closely linked to personality or temperament. More on the different conceptualizations of impulsivity will be outlined in the second chapter. For now, it could be outlined that an impulsive individual has behaviours that are not optimal (in regards of the situation or context) and that his behaviours are usually associated with negative outcomes or repercussions for himself or others. However, impulsivity can also be a positive or desirable act. This is further elaborated in the next sections.

Functional vs. Dysfunctional impulsivity

The definition of impulsivity can be extended with consideration of functional and dysfunctional impulsivity. As outlined above, impulsivity is generally associated with a negative connotation. Grayson and Tolman in 1950 already described impulsivity as behaviours associated with negative outcomes: low inhibitory control, actions done with little thinking, poor judgment, little planning or anticipation (Grayson & Tolman, 1950). It is understood as acting with little thought, having rapid and spontaneous actions, showing little inhibitory control, disregarding future consequences or having difficulties stopping an ongoing behaviour (Buss & Plomin, 1975; Dickman, 1990; Logan, Schachar, & Tannock, 1997; McCown, Johnson, & Shure, 1993). People who are risk-takers, show little patience or avoid long and monotonous tasks, are usually considered impulsive (Barratt, 1985; Hollander & Stein, 1995). This is also known as dysfunctional or negative impulsivity.

As stressed by Dickman (1990), however, impulsivity can also be a positive act, as actions generated with little forethought and control can also lead to positive outcomes (e.g. a person jumping fully clothed into a pool to save a child). Positive impulsivity is a sought-after skill. Making choices and taking decisions rapidly is observed in certain types of jobs like race-car drivers, military personnel, firefighters, policemen and stock traders.

Impulsivity can therefore be understood within two types: 1) functional or positive and 2) dysfunctional or negative (Dickman, 1990). When an individual reacts quicker and with more positive outcomes than individuals in the same situation, this person shows functional impulsivity. Dysfunctional impulsivity is the opposite: acting in a very rapid fashion, but with predominantly negative outcomes (Caci, Nadalet, Baylé, Robert, & Boyer, 2003). This thesis is limited to impulsivity associated with less than favourable consequences. When reading impulsivity, the reader should understand “dysfunctional” or “negative impulsivity” (and hence not promptness or efficiency).

Trait vs. State impulsivity

When assessing impulsivity, another distinction made is between stable (trait), and fluctuant (state) or event-related impulsivity. The predisposition (or trait) to act impulsively is closely linked to temper and personality (Buss & Plomin, 1975; Eysenck & Eysenck, 1978). Trait impulsivity has a negative influence on executive functioning (e.g. organization, inhibition and cognitive flexibility) and also affects information processing (Hollander & Stein, 1995). This specific type of impulsivity does not influence one particular subtype of impulsivity (i.e. motor, attentional or cognitive), but rather influences an individual's global functioning (Leshem & Glicksohn, 2007). These individuals show a relatively stable predisposition for novelty seeking behaviours (Webster & Jackson, 1997). This predisposition is either associated with low consideration for future consequences or carelessness or both. Being stable over time, trait impulsivity is usually assessed with self-completed questionnaires (e.g. Stanford et al., 2009). For example, the Eysenck Impulsiveness Questionnaire (Eysenck, Pearson, Easting, & Allsopp, 1985) was developed for this specific type of impulsivity.

State impulsivity is a brief and changing behaviour that is greatly influenced by a specific context (Logan & Cowan, 1984). According to Cyders and Smith (2008), state impulsivity can be triggered by both a positive or negative context. The causes of the impulsive act may be positive or negative, but the consequences (e.g. drug use, alcohol consumption, sexual promiscuity) are always predominantly negative, as seen above with Dickman (Dickman, 1990). State impulsivity is usually assessed with behavioural measures, as will be seen in the second chapter (for now, see Dougherty et al., 2005). The behavioural measures usually conceptualize impulsivity as a lack of inhibition (or disinhibition). Therefore, the different conceptions of inhibition will be explored next.

Inhibition

In this section, conceptualizations of inhibition are provided. As with impulsivity, there are multiple ways of conceiving inhibitory control (Lezak, 2004; Lezak, Howieson, Bigler, & Tranel, 2012; Miyake et al., 2000; Moeller et al., 2001; Verbruggen & Logan, 2009). Inhibition (or self-control) is a cognitive ability required to deliberately stop an ongoing activity, delay a response or withhold an action (Barkley, 1997; Enticott, Ogloff, & Bradshaw, 2006; Miyake et al., 2000). An uninhibited response is therefore a spontaneous act done without much thinking or constraints. Inhibition tasks usually put the individual in situations where he or she needs to withhold an action, evaluate the consequences or benefits of an action or where an action must be stopped to generate a new one (Barkley, 1997; Conners & Staff, 2000; Logan & Cowan, 1984). Inhibition of an ongoing response is the ability to refrain or control an automatic response (Miyake et al., 2000). Motor impulsivity is the consequence of poor behavioural disinhibition (or low behavioural inhibitory control), where less than appropriate response cannot be stopped (Enticott et al., 2006; Perales et al., 2009). Consequently, inhibitory control and impulsivity could be seen as opposites (Bickel, Jarmolowicz, Mueller, Gatchalian, & McClure, 2012). One of the most popular paradigm to assess control of inhibition is the Stop-Signal Task (Logan, 1994), which is also used to measure motor impulsivity (Logan, 1994; Miyake et al., 2000; Ray Li, Yan, Sinha, & Lee, 2008).

Despite the lack of consensus in the literature regarding conceptualization or taxonomy of impulsivity, inhibition is usually considered as a main component in executive functions (Chikazoe, 2010; Nigg, 2000; Verbruggen & Logan, 2009). Executive functions are complex cognitive abilities involved in handling new situations or responding adequately to daily demands, as opposed to known situations, which are thought to implicate memory and automatic responses (Kolb & Whishaw, 2009). Executive functions are responsible for everyday goal achievements and include abilities like organization, mental shifting, initiation, inhibition, planning and behaviour regulation (Gioia, Isquith, Guy, & Kenworthy, 2000; Lezak, 2004). Executive functions are a complex neural network involving not only the prefrontal cortex, but also the thalamus and basal ganglia, among others (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Disinhibition has been associated with impulsive behaviours (Enticott et al., 2006; Logan et al., 1997) and psychopathological disorders such as pathological gambling (Goudriaan, Oosterlaan, De Beurs, & Van Den Brink, 2006) or alcohol dependence (Noël, Bechara, Dan, Hanak, & Verbanck, 2007). More on this will be explored in the next section.

Impulsivity in psychiatry

Impulsivity is one of the most common symptoms of mental disorder diagnoses (i.e. tension - relief dynamics). It is closely associated, among others, with alcohol abuse (Littlefield, Vergés, Wood, & Sher, 2012), drug abuse (Sher, Bartholow, & Wood, 2000), oppositional or antisocial personality (Kay & Tasman, 2006), borderline personality (Crean, de Wit, & Richards, 2000; Newman, Kosson, & Patterson, 1992), and pyromania (Hollander & Rosen, 2000). As such, the fifth version of the DSM regroups disorders characterized by disinhibition or impulsivity under the umbrella of Impulse-Control and Conduct Disorders (i.e. intermittent explosive disorder, kleptomania pyromania, pathological gambling, sexual compulsions, compulsive shopping, skin picking, Internet addiction, and conduct disorders; see APA, 2013). Impulsivity *per se* is still not clearly defined, however (Figure 2 in Appendix A provides a diagnostic help to distinguish between mental disorders and manifestations of impulsivity). There is a rich history of fundamental psychological studies focussing on impulsivity as a personality component (e.g. Evenden, 1999).

Persons with disinhibition disorders share the irresistible urge to act in a given way. In psychiatry, reacting on an impulse is associated to both impulsion and compulsion (Wright, Rickards, & Cavanna, 2012). Compulsions are usually associated with a growing tension linked to repetitive actions or rituals (Kay & Tasman, 2000). According to Shapiro and Shapiro (1982), a sense of "rightness" guides an impulsion, while a compulsion is implemented to reduce anxiety associated with an obsession. Another distinction between the two concepts lies in the fact that the disinhibition observed in impulsions often has harmful consequences. These consequences can be for the individual (the self-destructing nature of trichotillomania, for example) or for his relatives and/or surroundings (hetero-aggressive behaviours such as pyromania or kleptomania; see Kay & Tasman, 2006). A third distinction is the deliberation process.

In obsessional behaviours (compulsions), the deliberation about an action is constant, time-consuming and sometimes never-ending. In impulsions, it is more sudden and precipitated (Kay & Tasman, 2006). Actions are here done with little thought or foresight.

Contrarily to popular opinion, individuals with severe mental illnesses are responsible for only 3-5% of all crimes (Dubreucq, Joyal, & Millaud, 2005). Large and colleagues (Large, Smith, & Nielssen, 2009) estimated that only 6% of all homicides were committed by individuals suffering from a psychotic disorder (including schizophrenia). It is the minority of them (less than 10%) that are causing the majority of the violent acts. The remaining 90% of individuals with severe mental illnesses show little to no aggressive behaviours. The considerations of how to assess impulsivity in a forensic context will be outlined in Chapter 2.

Summary of this section

In conclusion, impulsivity is not unitary construct. Furthermore, this concept is divided in functional vs. dysfunctional impulsivity, as well as state vs. trait impulsivity. This thesis concerns only dysfunctional impulsivity. The second chapter of this thesis will further evaluate conceptualizations of impulsivity and provide an inclusive definition of impulsivity. Practical implications of the assessment of impulsivity will also be addressed.

Given its multicomponent construct, it comes as no surprise that few single measures of impulsivity are currently available. Neuropsychological assessment is typically used to assess an individual's level of impulsivity. Traditionally, this was achieved with paper-pencil tasks or questionnaires, although there are doubts that current instruments can truly predict behaviour, especially if impulsive (Burgess et al., 1998; Drouin-Germain et al., 2012; Henry et al., 2013a). Furthermore, no recent and widely recognized publication addressing this problem could be found. Thus, there are currently two main problems for clinicians confronted with impulsivity: it is ill-defined, and no single measure is adequate. This will be outlined in the next chapter. A critical review of the available instruments to assess impulsivity is also provided in Chapter 2. Next, VR as an assessment method will be explored.

Virtual reality

This section focuses on VR as a technology that can be used for assessment and intervention. First, a definition of VR is provided. The use of virtual reality in clinical and research settings is also outlined. Second, the main key concepts of VR are discussed. The current and most commonly used equipment to generate and record VR are reviewed. Lastly, the advantages of using VR will be explored.

Historical aspects of virtual reality

Virtual reality has changed greatly ever since it was first introduced. The diverse apparatus used today date back to inventions from the late 1960s. Technological developments such as stereoscopic television or wide motion screen displays were all milestones in this field (see Sherman & Craig, 2002). Sutherland is thought to be one of the first VR apparatus developer with his “ultimate display” (Sutherland, 1968). This technology later evolved into the Head-Mounted Display (HMD). A similar technology was created by Comeau and Bryan in 1961, but received less support (see Sherman & Craig, 2002).

The team of Sutherland also developed the first VR system based on augmented reality. The “Sword of Damocles” combined virtual objects to the real world (Sutherland, 1965, 1968). This system helped popularize VR in the research field (Sherman & Craig, 2002; Zimmerman, Lanier, Blanchard, Bryson, & Harvill, 1987). Jaron Lanier also helped promote VR in the late 1980s by introducing the first avatars (for a review, see Riva, 2005).

At the same time, movement trackers were also introduced (Defanti & Sandin, 1977). It was then possible to record and interpret certain body postures or hand movements with the help of a computer. In 1989, Nintendo© launched the *Powerglove*, which did not have much success in the gaming world, but rapidly became a cheap tool for scientists. Realistic gaming also grew significantly in those years. In 1990, the first arcade gaming systems using HMD technology were put on the market (Sherman & Craig, 2002). The late 1990s also saw many technological developments. DisneyQuest and various arcades started using technologies such as augmented displays and HMD.

The CAVE (from the Swedish Royal Institute of Technology) and the VR-CUBE (from the TAN Projektions technologie GmbH & Co. in Germany) were also introduced. Both the CAVE and the VR-CUBE are immersive experiences where the environment is projected on the walls in a cubed shaped room.

Virtual reality research grew to a remarkable level in the past 10 years. This is witnessed in the number of publications. From nearly 1,000 articles found on this topic in 2005 (Riva, 2005), now more than 6,389 articles are found, 2,178 of them from 2012 onwards (quick search query with keywords "virtual reality", on PsychINFO, accessed August 19th 2015). Next, a definition of VR as it is used in this thesis will be provided.

Definition of VR

Virtual reality is a technology that provides an environment and also relies on computational equipment to merge data such as position markers, participant responses and information about an ongoing task. Typically, visual and auditory stimulations are provided and the computer records information from position trackers (for example, from the head, the eyes or the hand), generates a three-dimensional visualisation, and incorporate the virtual reality environment (VRe) through HMD glasses, a Cave Automatic Virtual Environment (CAVE) or a dome (see Riva, 2005). These data are then combined into a simulated world. Virtual reality is more than a mere gathering of stimulation equipment. It also allows people to *interact* with a VRe in real-time (McCloy & Stone, 2001; Rubino, Soler, Marescaux, & Maisonneuve, 2002; Székely &

Satava, 1999). Participants here are more than observers. They engage in the VRe and are expected to interact with it (Riva, Molinari, & Vincelli, 2002; Schultheis & Rizzo, 2001). With VR, it is possible to provide participants with an alternate reality; whether it is with a VRe or an alternate world as it is the case with augmented reality (Sherman & Craig, 2002). Next, the use of VR in both research and clinical fields will be outlined.

The use of virtual reality in clinical and research settings

This section will outline that virtual reality is a reliable treatment option in psychotherapy, particularly with anxiety-related disorders. It is also a reliable and valid assessment tool for cognitive functions.

VR has been successfully used with most age groups; children (Adams, Finn, Moes, Flannery, & Rizzo, 2009; Nolin, Martin, & Bouchard, 2009; Rizzo et al., 2011), teenagers (Drouin-Germain et al., 2012; Fournier, Durocher, Drouin-Germain, Henry, & Nolin, 2011; Lalonde, Henry, Drouin-Germain, Nolin, & Beauchamp, 2012, 2013; Jacoby et al., 2013), adults (Baumgartner et al., 2008; Grenier et al., 2014; Henry, Joyal, & Nolin, 2012; Henry, Nolin, Drouin-Germain, & Joyal, 2011; Matheis et al., 2007; Thornton et al., 2005) and elderly (Allain et al., 2014; Nolin, Banville, Cloutier, & Allain, 2013; Nolin & Boucher, 2011). A growing number of virtual neuropsychological assessments have been developed and validated. Examples of such cognitive virtual-based assessments include: attention (Larson et al., 2011; Law, Logie, & Pearson, 2006; Lengenfelder, Schultheis, Al-Shihabi, Mourant, & DeLuca, 2002; Moreau, 2006;

Moreau, Guay, Achim, Rizzo, & Lageix, 2006; Parsons, Bowerly, Buckwalter, & Rizzo, 2007; Parsons & Rizzo, 2008c; Rizzo et al., 2000, 2006; Stipanicic et al., 2011), memory (Allain et al., 2014; Astur et al., 1998; Astur, Tropp, Sava, Constable, & Markus, 2004; Brooks et al., 2002; Knight & Titov, 2009; Matheis et al., 2007; Parsons & Rizzo, 2008b; Plancher, Gyselinck, Nicolas, & Piolino, 2010; Plancher, Tirard, Gyselinck, Nicolas, & Piolino, 2012; Sweeney, Kersel, Morris, Manly, & Evans, 2010), spatial abilities (Astur et al., 1998, 2004; Beck et al., 2010; Moffat, 2009; Moffat, Zonderman, & Resnick, 2001) and executive functions (Armstrong et al., 2013; Baumgartner et al., 2008; Baumgartner, Valko, Esslen, & Jäncke, 2006; Cao, Douguet, Fuchs, & Klinger, 2010; Elkind, Rubin, Rosenthal, Skoff, & Prather, 2001; Jovanovski, Zakzanis, Campbell, Erb, & Nussbaum, 2012; Law et al., 2006; McGeorge et al., 2001; Pugnetti et al., 1998; Raspelli et al., 2009; Riva, 2010; Zalla, Plassiart, Pillon, Grafman, & Sirigu, 2001).

The advantages of VR have also been demonstrated in the field of neuropsychological rehabilitation (Penn, Rose, & Johnson, 2009; Rose, Brooks, & Rizzo, 2005; Wang & Braman, 2009; Wang & Reid, 2011). Moreover, it has been used with many clinical populations such as: ADHD (Adams et al., 2009; Bioulac et al., 2012; Bowerly, 2002; Parsons et al., 2007; Pollak, Shomaly, Weiss, Rizzo, & Gross-Tsur, 2010; Pollak et al., 2009) autism spectrum (Mitchell, Parsons, & Leonard, 2007; Parsons & Cobb, 2011; Pierre & Stipanicic, 2012; Wang & Reid, 2011), neurofibromatosis (Gilboa, Rosenblum, Fattal-Valevski, Toledano-Alhadef, &

Josman, 2011), traumatic brain injury (Martin & Nolin, 2009; Penn et al., 2009; Zhang et al., 2001), sport concussions (Nolin et al., 2012; Nolin, Stipanicic, Lachapelle, Lussier-Desrochers, & Henry, 2011), brain damage (Rose et al., 2005), eating disorders or obesity (Bouchard, Aimé, & Monthuy-Blanc, 2013; Riva, Bacchetta, Baruffi, Rinaldi, & Molinari, 1998; Riva, Bacchetta, Cesa, Conti, & Molinari, 2001, 2003), male erectile dysfunctions (Optale et al., 1997, 1998, 1999) and post-traumatic stress disorder (Rothbaum et al., 1999; Rothbaum, Hodges, Ready, Graap, & Alarcon, 2001). Assessments here mimic real-life events such as cooking (Cao et al., 2010; Yamaguchi, Foloppe, Richard, Richard, & Allain, 2012), shopping (Jacoby et al., 2013; Rand, Weiss, & Katz, 2009; Raspelli et al., 2012), going to school (Lalonde et al., 2013; Nolin, Banville et al., 2013; Nolin et al., 2009) or going to a library (Renison, Ponsford, Testa, Richardson, & Brownfield, 2012), to name a few.

Virtual reality is also known to have great success in psychotherapy (Gamberini & Spagnolli, 2005). The advantages of VR have been documented in clinical therapy of public speaking (Lee et al., 2002; North, North, & Coble, 1998) natural phobias such as acrophobia (Emmelkamp et al., 2002; Emmelkamp, Bruynzeel, Drost, & van der Mast, 2001), aviophobia (Maltby, Kirsch, Mayers, & Allen, 2002; Rothbaum et al., 2006; Rothbaum, Hodges, Anderson, Price, & Smith, 2002; Rothbaum, Hodges, Smith, Lee, & Price, 2000; Wiederhold et al., 2002), animal phobias such as arachnophobia (Garcia-Palacios, Hoffman, Carlin, Furness III, & Botella, 2002), agoraphobia (North, North, & Coble, 1996; Vincelli et al., 2003; Vincelli, Choi, Molinari, Wiederhold, & Riva, 2000;

Vincelli, Molinari, & Riva, 2000), situational phobias like claustrophobia (Botella et al., 1998), pain management (Gershon, Zimand, Lemos, Rothbaum, & Hodges, 2003), intellectual disabilities (Standen & Brown, 2005), driving abilities (Lengenfelder et al., 2002; Rizzo, Schultheis, Kerns, & Mateer, 2004; Schultheis & Mourant, 2001), empathy (Bouchard, Bernier et al., 2013), and the influences of mood on body image (Tremblay et al., 2013), to name a few.

As seen above, VR therapy is particularly popular with anxiety-related disorders. The client can here gradually face the feared scenario and lower his anxiety or discomfort over time with habituation and extinction. This is an appealing technique to do exposition therapy for clinicians since these treatments are not only efficient, but also cost-effective (Riva, 2005). Furthermore, benefits from the VR therapy are documented to have long-term and lasting effects (Rothbaum et al., 2002, 2006; Wiederhold & Wiederhold, 2003).

Virtual reality is also a helpful tool to generalize learning in individuals that have limited cognitive ability (Rizzo & Kim, 2005). For example, Cromby and colleagues found that teenagers with severe learning disabilities that had a virtual training were quicker in doing shopping errands than those who did not have such a training (Cromby, Standen, Newman, & Tasker, 1996). Virtual reality also improved performances in pain management (Das, Grimmer, Sparnon, McRae, & Thomas, 2005), hand rehabilitation (Boian et al., 2002), hearing impaired children (Passig & Eden, 2001), cerebral palsy

(Reid, 2002), Parkinson's disease (Riva, 2010), traumatic brain injury (Larson et al., 2011) and autism (Mitchell et al., 2007; Strickland, Marcus, Mesibov, & Hogan, 1996). Stroke patients also showed promising results. They were able to transfer acquired safety skills from virtual to real life, and showed better multi-tasking capabilities than the control group (Katz, Hartman-Maeir, & Katz, 2005; McGeorge et al., 2001; Rand et al., 2009). Similar results were also obtained from Cao and colleagues in their virtual kitchen (Cao et al., 2010).

In conclusion, the usefulness of VR as an assessment tool is no longer under debate. Also, the evidence that it can successfully be used as a therapeutic or clinical approach is immense. This superiority of VR could be explained by its ecological validity. The next section will show that VR provides, via immersion, a multidimensional human-computer environment that has both proximal and contextual cues (Carvalho, Freire, & Nardi, 2010). This technology can provide situations with a control and/or intensities that are impossible or hard to get in real life. An invasive or uncomfortable virtual experience could diminish the inclusive aspect of the task. This could have a negative influence on the immersion (Slater, 2002). To better understand the strengths and limitations of VR, four components in VR experience: ecological value, immersion and sense of presence and cybersickness are discussed next.

Main components in VR experience

A crucial goal when working with VR is to have the participant engaged in the ongoing task. This is usually done with the help of the sensory feedback and the interactivity provided by the technology used (Sherman & Craig, 2002). This helps the VRe seem authentic and believable and help create an inclusive experience in which the participant can fully focus on the VRe. The level to which the participant will be absorbed in the task is called sense of presence and will be explained in this section. Other important variables such as immersion and cybersickness will be discussed as well. First, ecological value will be explored.

Ecological value. Traditional assessments lack sensitivity and predictive value (Burgess et al., 1998). These tests were developed as diagnostic help or to understand a patient's limitations, and not to predict behaviours (Long & Kibby, 1995). To alleviate this problem, it was proposed that assessments should be conceptualized in regard of their ecological value (Sbordone, 2008). Ecological value refers to the sameness of the results obtained on a given test and those obtained in the natural environment of the patient (Tupper & Cicerone, 1990). For the task to yield behaviours that are common or expected in day-to-day life, the task used to assess the client should be close to something that the client is familiar with (Marcotte & Grant, 2009). Ecological value does not mean that the test is necessarily valid, but that the conclusions drawn from the test are (Franzen & Arnett, 1997; Heinrichs, 1990). It is thought that in those cases, predictive validity is superior to traditional tasks (Sbordone, 2008).

A review of the literature on traditional assessments showed that they have a low to moderate ecological validity (Chaytor & Schmitter-Edgecombe, 2003). Virtual reality is thought to be an ecological alternative to assess cognitive functions (Riva, 2005; Spooner & Pachana, 2006; Titov & Knight, 2005). Two variables are important when deciding if an assessment is ecologically valid: veridicality and verisimilitude, which will be addressed next. In the literature review mentioned above (Chaytor & Schmitter-Edgecombe, 2003), tasks that fell in these two categories were linked to higher ecological value.

Verisimilitude. This concept refers to the congruence between the cognitive ability measured in the test and the ability required in real-life to do a similar task (Franzen & Wilhelm, 1996). Verisimilitude tests therefore aim at resembling day-to-day activities. The *Test of Everyday Attention* (TEA, McAnespie, 2001; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994), the *Test of Everyday Attention for Children* (TEA-Ch , Manly, Robertson, Anderson, & Nimmo-Smith, 1999), the *Rivermead Behavioral Memory Test* (RBMT, Wilson, Cockburn, & Baddeley, 1985) and the *Behavioral Assessment of the Dysexecutive Syndrome* (BADS, Wilson, Krabbendam, & Kalff, 1997) are congruent with this concept. They are thought to be more ecological than other traditional assessments (Higginson, Arnett, & Voss, 2000; Makatura, Chow, Lam, Castillo, & Kalpakjian, 1999).

The close resemblance of a task to a real event is a positive feature and could help with behaviour prediction. It is, however, not sufficient as it is also important to be able to understand, discriminate and diagnose. Assessments that are similar to daily activities are not necessarily good at this, and hence could lack rigor. This is where veridicality comes into play.

Veridicality. Veridicality refers to the predictive value of traditional tests (Franzen & Wilhelm, 1996). When a test shows great veridicality, the conclusions drawn from it are expected to be close to what we would expect to see in the client's real-life. Even so not all tests are conceptualized with veridicality in mind, statistical analyses can help establish the veridicality of a test post-hoc. This is, however, hard to establish in some cases as the tasks were built for diagnosis purposes and not necessary for predictive value. Furthermore, assessing real-life situations can be challenging. Assessments used would also have their own measurement errors, which would limit the use of statistics.

In summary, a good ecological task would be a real-life situation known to the patient and be both true to his functioning and able to predict behaviour. Another important component of VR is the ability (and necessity) to be engaged to the ongoing task. This will be explained next.

Immersion and Sense of Presence. A first distinction should be made between immersion and presence. The first typically refers to the technological quality of the

VRe, whereas the latter refers to the sensations or feelings coming from that VRe (Slater & Wilbur, 1997). Better immersion means that the environment is realistic or believable and hence, facilitates sense of presence (Gorini, Capideville, De Leo, Mantovani, & Riva, 2011).

The immersion experience can be categorized in two ways: a physical and/or a mental immersion. Physical immersion in VR comes from the technology used to stimulate senses and increase the realistic experience. Mental immersion refers more to the experience of feeling the immersion or believing what is happening. This is also referred to as sense of presence (Sherman & Craig, 2002). According to Slater and Wilbur (1997), an immersive environment is able to elicit a wide range of sensory input and distract the participant from real life. In other words, the VRe becomes extensive and inclusive. The participant here feels enclosed in an environment that is broad (also called surrounding properties of a VR task). This can be helped with a wider display (e.g. panoramic view from an elliptic television or a CAVE). The image display, sounds, and the information provided during the VR experience should be of great quality so that it matches what the subject expects (also known as vivid and matching components) (see Riva, 2005). These factors (extensive, inclusive, surrounding, vivid and matching) are fundamental to elicit a greater sense of presence (Sherman & Craig, 2002). If the system lags (low matching) and the visual quality are rather poor (low vividity), the subject will spend cognitive efforts on trying to understand the VRe. If the display is rather good, the visual accommodation will be lesser and cognitive responses will be more representative

(Ellis, 1991). When the VRe is very immersive, it outperforms the appeal of the real world and the participant gets engaged more in the virtual experience than the surroundings. This feeling of being "there" in the VRe or living outside of the self is the core of sense of presence (Riva, Davide, & IJsselsteijn, 2003; Steuer, 1992).

Sense of presence is a conscious feeling that the events taking place in the virtual environment are or could be real (Slater & Wilbur, 1997). Rather than just looking at a computer screen and images roll by, the participant forgets about the technology and equipment and engages in the task (IJsselsteijn, de Ridder, Freeman, & Avons, 2000; IJsselsteijn, Ridder, Freeman, Avons, & Bouwhuis, 2001; Lombard & Ditton, 1997). When sense of presence is very high, the participants can forget about the experiment, the lab-settings, the equipment and the experimenter (Baumgartner et al., 2008). Some participants even talk out loud to the avatars or try to interact with the objects. This was the case for some of the participants assessed with the VRes of this thesis. Adults would seldom express their frustration, whereas adolescents tried to interact (talk or touch) the other children avatars in the virtual task.

Propension to immersion. Individual differences can also be observed in sense of presence, which refers to propension to immersion. That is the ability to concentrate, to be more or less involved or absorbed (in sport events, movies or books for example). Propension of immersion can mediate the effectiveness of VR (Emmelkamp, 2005; Wiederhold & Wiederhold, 2000). Individuals that have a greater propension to immersion are more likely to be immersed in movies or novels. This is called mimesis, referring to the action of getting submerged in a story. Individuals who show mimesis are thought to be easily and rapidly engaged in the VRe (Sherman & Craig, 2002).

Sense of presence is also an objective experience and considered by some as a neuropsychological ability (Mantovani & Riva, 1999; Riva, Davide et al., 2003; Schubert, Friedmann, & Regenbrecht, 2001; Slater, 2002; Slater & Wilbur, 1997; Steuer, 1992; Waterworth & Waterworth, 2001, 2003; Zahorik & Jenison, 1998). As mentioned above, the behaviours and reactions observed while a participant interacts with the VRe should be similar to how he would react in the real world. These reactions can and should be measured with sense of presence.

Assessment. One option when considering assessment of sense of presence is behavioural measures, such as skin conductance (Wilcox, Allison, Elfassy, & Grelik, 2006). These authors found that participants had negative physiological reactions when the VRe did not behave as they thought it should. Electrodermal activity changed in cases where their personal space was violated, when the programmed lagged or if their avatar went through an object. For the authors, this was believed to show that the person was engaged in the task and the stress reaction was linked to something unexpected happening. Individuals who showed little responses or who purposefully did improbable actions (running into a wall for example) were thought to have very little sense of presence and not fully engaged in the task.

Other physiological or behavioral responses such as fidgeting or crying are also thought to be good predictors of presence (Hoffman, 2009). According to Riva (2005), VR can induce emotions. It is believed that the immersion can induce emotions comparable to what would be shown in a similar real-life situation. It also allows the participants to experience alternate versions of themselves (North, North, & Coble, 1997; Perpiñá et al., 1999; Vincelli, 1999; Vincelli, Molinari et al., 2000). These authors also go a step-further and say the VRe should trigger emotions or reactions in the individual to reach a high level of presence. They also believe that the sense of presence is important in clinical studies and mediates the positive outcomes of the therapy.

Sense of presence can also be measured with self-reported questionnaires. Many different versions have been validated throughout the years: the *Igroup Presence Questionnaire* (Schubert et al., 2001), the *ITC-Sense of Presence Inventory* (Lessiter, Freeman, Keogh, & Davidoff, 2001), the *MEC-Spatial Presence Questionnaire* (Wirth et al., 2003) and the *Presence Questionnaire* (Witmer & Singer, 1998). Because it was translated and validated in French, the *Presence Questionnaire* was used in the current thesis (Robillard, Bouchard, Renaud, & Cournoyer, 2002).

In summary, for assessment and therapy, VR needs to be close to the day-to-day life of the participant or a situation that is believable. Additionally, the technology used should be non-invasive and provide a believable experience.

Cybersickness. Cybersickness is an important variable to consider when doing VR as it can greatly alter sense of presence and performance. These signs are caused by a sensory conflict linked to the technology used (Kim, Kim, Kim, Ko, & Kim, 2005). The symptoms associated with cybersickness are similar to what an individual could experience with motion sickness (e.g. nausea, headache, fatigue, difficulty focusing) (see Sherman & Craig, 2002). The conflict lies between a sensory mismatch of the movement information between eyes and vestibular system. The eyes receive information about a moving and interactive situation, while the vestibulatory system is motionless (Kingdon, Stanney, & Kennedy, 2001; Stanney, Kingdon, Graeber, & Kennedy, 2002). Luckily, cybersickness is relatively rare in the general population (see Lawson, Graeber, Mead, & Muth, 2002). The symptoms associated with cybersickness are often studied when doing VR research as they can abruptly stop an ongoing experiment. One technique to alleviate cybersickness is to give the participant a time of adaptation (Riva, 1997). This can be done by doing a trial, where one can familiarize himself with the apparatus, environment and contingencies of the VR task (LaViola, 2000). This was done for all experiments in this thesis.

Improving quality of the immersion and sense of presence

As outlined above, efforts were made in recent years to increase qualities and properties of VRes. The quality of the immersion is often thought to be an important factor for sense of presence (IJsselsteijn et al., 2001). Results on this are, however, mixed. According to Regenbrecht and colleagues, there is a relationship between graphic quality and the sense of presence (Regenbrecht & Schubert, 2002; Schubert et al., 2001). It is however argued that the graphical quality of the task could lead to better task performances, but not necessarily better sense of presence (Dinh, Walker, Hodges, Song, & Kobayashi, 1999).

Another important factor is stereoscopy or the "3D-like" effect. This is thought to be primarily related to sense of presence (Baños et al., 2008). However, findings by Hoffman and colleagues (Hoffman et al., 2006) point to the fact that it may not be the three-dimensional aspect that is relevant, but the scope or field-of-vision. Participants that had a bigger angle to look at were more engaged, and hence had greater sense of presence. This could be a limitation of using a HMD as it only offers a 40-degree field of view (Reger & Gahm, 2008). Furthermore, eye fatigue is often associated with the use of a HMD. Regardless of this, HMD is the number one apparatus paired with VR (Riva, 2005), still to this day.

The use of the "infinite floor" is another example of technologies that are used to increase sense of presence. This apparatus is believed to be one of the easiest and most successful option to dramatically increase the matching component of immersion (Slater, Steed, & Usoh, 1995). This could also decrease cybersickness as there is better congruence between the proprioceptive system and the visual cortex (Slater & Wilbur, 1997). However, the space required for such a device and its price limits its appeal (Iwata, 1999; Torrell, 2012).

The capability of a technology to submerge is also a good predictor of sense of presence. The CAVE is believed to be linked to a higher sense of presence as compared to a HMD. The CAVE has a 360 degrees visual stimulation without the need of any intrusive equipment. Furthermore, it can deliver spatial acoustic stimulation (Krijn, Emmelkamp, Olafsson, & Biemond, 2004). This does not however always translate to better performances or better therapeutic outcomes (Emmelkamp, 2005).

Sense of presence is not limited to the technology used, but how believable the experience is in general (Karaseitanidis et al., 2006). Sense of presence is a subjective experience (Slater & Wilbur, 1997) and is heightened when auditory, olfactory or sensory cues are present (Dinh et al., 1999). Adding sounds, vibrations in the chair or textural and tactile stimulations can help the participant feel more "there".

Equipment

As the aim of this thesis is to develop a novel assessment of impulsivity in VR, it is necessary to evaluate current technologies. The purpose of this section is to reach a conclusion of which technology could or should be used. This section will discriminate between four main components that VR assessments should have: 1) the ability to stimulate (hardware); 2) the ability to track the subject's behaviours; 3) the ability to real-time process participant's information and adjust the stimulation (software); and 4) the ability to measure other dependent variables.

Stimulation hardwares. The majority of VR experiments rely primarily on a visual immersion. The HMD is the most used apparatus in the VR field, but other options also are possible. They are dependent on the objectives of the study, the available technology, the portability or possible mobility, and the cost. Some of the available options will be listed below.

Static display - Fishtank. In this particular case, the VRe is projected on a television or computer screen. This is also referred to as fishtank VR (Sherman & Craig, 2002). This type of display is inexpensive and very compelling for many clinical populations. It is however argued by some as whether it is VR at all, as this gives little realism and could decrease sense of presence (Gorini et al., 2011). It is known that immersion is lesser with this method, as the participant still has cues from the surrounding environment in his peripheral field. However, the lack of wires and apparatus can sometimes be an advantage (Sherman & Craig, 2002).

Static display – Projection. This display is typically used inside a CAVE or a CUBE. Some say that it is the best technology to be able to elicit a complete immersion (Lantz, 1996). Participants can lose all references to the outside world (this is usually the case for 4 projected panels and more). With projection based displays, participants can freely move in the VRe. It also gives a wide angle where the VRe is showed. Besides the cost (which is usually the main negative concern), projection displays can also produce occlusion errors. Occlusion errors happen when an object is wrongfully represented in the environment. Its physical properties (e.g. height, shape) can become distorted or the object can overlay something that was meant to be in the background. This can be confusing for the participant and can interfere with sense of presence or create a visual conflict. This, mixed with the mobility of the participant, can lead to a high potential for cybersickness (Sherman & Craig, 2002).

Head Mounted Display (HMD). Head Mounted Display (HMD) is an affordable and easy to use technology. The HMD allows participant to be visually immersed. A headband or helmet is mounted on the participant's head and the visual display is projected on two small screens (one for each eye). This recreates a stereoscopical effect. Typically, most HMD come with a head-tracking device that records head movements and shifts the VRe accordingly. The participant can therefore "look around" in the VRe similar to what he or she would instinctively do in real-life, making this technology intuitive and somewhat natural (Sherman & Craig, 2002). This is thought to increase the sense of presence. The HMD display can be occlusive or nonocclusive (see-through). The see-through HMDs are typically used in augmented reality with technologies such as the Magic Lense (Bier, Stone, Pier, Buxton, & DeRose, 1993) or the Google Glasses (Bilton, 2012). The HMD are easy to set up, non-invasive and a rather inexpensive technology. It can also be easily paired with other tracking apparatus, for example a glove. This was the technology used in the experiments of this thesis.

Handheld displays. With cellular phones, laptops and tablets becoming more available, handheld VR is the immerging technology of the future (Basu & Johnsen, 2014). Here, the VRe is typically displayed on a tablet or on a smartphone, sometimes with the use of stereoscopic glasses. Hand display are also widely used for augmented reality (Santos, Terawaki, Taketomi, Yamamoto, & Kato, 2015). With this, VR will be brought in situations where all the wires and apparatus of the previous years could not be taken. The future will tell us if this technology will surpass the others presented in this section.

Tracking. To provide a real-time feedback on the actions of a subject, it is necessary to monitor those actions and movements. Position trackers are amongst the most commonly used, typically with one of these six methods. For a detailed discussion on this technology, see Sherman and Craig (2002).

1) Electromagnetic fields. With the help of coils and antennas, the computer can know when the participant is farther away (as the signal gets weaker) and adjust the VRe accordingly;
2) Mechanical tracking. This technique is more invasive as the participant is strapped inside a contraption that gets stretched with each movement;
3) Ultrasonic tracking. Ultrasounds are sent at a precise time interval and the echo from a reflector is recorded. The computer is then able to assess the position of the participant by calculating the distance between the transmitter and the receiver;

4) Inertial tracking. This technique uses accelerometers that record movements and inclinations. This is the same technology used in gaming consoles, the Wii remote for example (Lee, 2008);
5) Neural or muscular tracking. Sensors are here attached to extremities (e.g. fingers) and responses are sent to the computer and translated into the according bodily movement;
6) Visual tracking. Movements are recorded with one or more camera and the help of salient or colourful items. One device that uses this type of tracking is the IREX from GestureTek (see www.gesturetekhealth.com/products-rehab-irex.php). This VRe is mainly used with rehabilitation patient. The participant here can move freely and a loop-camera system projects his body in the VRe. With this particular apparatus, participant can, for example, mimic flying by flapping their arms or holding them still for gliding.

Stimulation software. Foremost, VR software has to provide the VRe usually via a visual stimulation. The stimulation is dependent on the behaviors and position of the participant. That is, the software has to derive the current stimulation from the intended VR and the participant's gaze direction and other position information. This means that the stimulation is dependent on the subject's behaviors. Usually, the software has a static (e.g. the projected virtual room) and a dynamic component (e.g. other avatars). Additionally, the software can have the purpose of control timing and interaction with other devices and record various data (Sherman & Craig, 2002).

Most VRes are tailored to the research objectives (like it was the case in this thesis). Some VRe software are free of charge and open-source. NeuroVR is a good example (www.neurovr2.org). The task used in this thesis (ClinicaVR: Apartment-Stroop) was inspired by Rizzo's virtual classroom and developed by the team of Digital Media Works (www.dmw.ca). The ClinicaVR: Apartment-Stroop (referred to as the VR-Stroop in this thesis) was developed to assess impulsivity and attention with adults, while immersing them in an apartment filled with distractors. More on this task can be found in the Appendix B and in Chapter 4.

Outcome measures. All the above-mentioned tracking technologies do provide dependent variables or outcome measures of the experiment, particularly about movements. However, sometimes researchers are interested in further dependent variables. Additional measurement technology is commonly used in VR. Here are the most common ones.

Gaze measures. Typically, little cameras detect where the face or the eyes of the participant are. This can be easily done with eye-trackers Tobii (www.tobii.com), ASL (www.asleyetracking.com), FaceLAB (www.seeingmachines.com) or SMI (www.smivision.com). Most of this equipment also merges eye-tracking data with other facial components like the movements of the mouth, the position of the nose and the reactions of the eyes (blinking, pupil dilatation to name a few).

Other physiological measures. In some experiments, it is assessed if a participant fidgets on the chair during the experiment or becomes uncomfortable. The wiggle cushion or a respiration belt are good examples of technologies used to do so (see www.toughttechnology.com). In forensic cases, assessing sexual offenders for example, sensors are used to track arousal with penile strain gauge or vaginal plethysmograph (see www.limestonetech.com). Others could be interested in what happens in the brain and would record brain electrical activity with electroencephalography (EEG) (see for example www.brainproducts.com).

The advantages of choosing virtual reality

There are many advantages of choosing VR in both assessment and treatment. This section will show that VR is rigorous, safe, enjoyable and relatively cheap.

As it was seen above, VR has components that make the experience more ecologically valid than traditional paper-pencil task. When compared to traditional assessments, VR can control for additional variables and parameters that are usually not accessible. It can assess multiple cognitive abilities simultaneously (and without the participant noticing it). In fact, participants often forget the equipment and apparatus, and get immersed in the ongoing task. This supports Parsons' proposition that VR is a unique but efficient way to assess different cognitive abilities (Parsons et al., 2007, 2015). Virtual reality is also consistent (Riva, 1997). The presentation of the stimuli is always the same and every variable is controlled. Virtual reality is therefore a rigorous and great methodological assessment for neuropsychologists (Parsons et al., 2015).

Virtual reality is also a safe and useful tool for both intervention and research. Participants are able to gage their interaction with the VRe and react accordingly in a non-harmful or threatening environment. With VR, participants are immerged in a VRe that would not otherwise be accessible in real life, due to resources, costs, distance or even safety (Winn, Windschitl, Fruland, & Lee, 2002). Assessing individuals with VR can hence overcome many dangerous problems. The Multiple Errand Test (Knight, Alderman, & Burgess, 2002) is a good example. Sending elders suspected of having dementia or Alzheimer to do some shopping is a risky task that could have severe complications (e.g. losing the participant). The same could be said about automobile driving skills (Lengenfelder et al., 2002; Schultheis & Mourant, 2001; Schultheis, Rebimbas, Mourant, & Millis, 2007; Wald, Liu, & Reil, 2000), where it is safer for the participant (and the general population) to assess driving skills via a computerized machine.

Virtual reality is a good approach to learn the relationships between abstract concepts in population with limitations (Dass, Dabbagh, & Clark, 2011; Girvan & Savage, 2010; Wang & Braman, 2009). Virtual reality can also side-step some ethical problems in assessment. The assessment of sexual offenders is a good example. Avatars of adults can here be shrunk into children size. The stimulus therefore looks like a youngster, but is based on an adult body (Renaud et al., 2009, 2010, 2011, 2013, 2014). This makes assessing pedophilia more accessible and ethically possible while having stimuli that are anatomically-corrected characters generated by a computer.

Another advantage of VR is that participants often enjoy the VR experience. A study by Garcia-Palacios and colleagues found that more than 80% of clients preferred the VR experience over the in vivo exposure in a therapeutical context (Garcia-Palacios, Hoffman, Kwong See, Tsai, & Botella, 2001). With VR, patients can explore and gradually face their fear or learn to do a task without fearing for themselves. Cognitive behavioural therapy and in vivo exposure are known to be gold standards in anxiety and phobias (Barlow, Raffa, & Cohen, 2002), but VR also shows promising results (Garcia-Palacios et al., 2001). Additionally, the VR task can also be stopped at any moment. This is thought to be very empowering for participants (Riva, 2005). Considering that nothing bad or harmful can happen to them, participants can enjoy and explore the VRe (Botella et al., 1998). Moreover, participants usually have very positive feedback about their VR experience (Riva, 2005). It has been documented that in vivo exposure combined with imagining phobic scenarios is as effective as in vivo therapy (Foa, Steketee, Turner, & Fischer, 1980; Rentz, Powers, Smits, Cougle, & Telch, 2003). A meta-analysis done by Powers and Emmelkamp (2008) showed that VR therapy of anxiety had large mean effect sizes when compared to control conditions. They also found that VR therapy was as effective as in vivo exposure. Virtual reality can also be used in patients that are too scared or phobic to face their fears (Botella, 2005).

Another argument for VR is its low cost and high practicality. As seen above, when VR is used for intervention purposes, it puts participants in contact with their fears. It is expected that they will slowly overcome their anxiety and gradually master the adverse physical and psychological reactions (Barlow et al., 2002). This extinction method can however be very pricey for some particular fears if treated with exposition in the real world. This is the case for avio- or aerophobia (the fear of flying). Virtual reality exposure therapy is a practical treatment option for fear of flying and does not require chattering a plane, pilots and crew members (Glantz, Durlach, Barnett, & Aviles, 1996). It also shows great results (Wiederhold & Bouchard, 2014a, 2014b).

Developing a VRe can however be expensive. Luckily free platforms are available. NeuroVR, which was developed by Riva and his colleagues (Riva et al., 2007) is a good example (see www.neurovr.org). Freeware are also available for augmented reality, such as the ARtoolKit (see www.hitl.washington.edu/artoolkit). Because they are easily customizable, one VRe can be used for a variety of clinical diagnostics. For example, virtual classrooms can be used to assess impulsivity and attention (Adams et al., 2009; Bowerly, 2002; Moreau et al., 2006; Nolin et al., 2009; Parsons et al., 2007; Rizzo et al., 2000, 2006), ADHD (Adams et al., 2009), neurofibromatosis (Gilboa et al., 2011) or even social phobias (Anderson, Rothbaum, & Hodges, 2003). Some environments such as the Iraqi war inspired Humvee Task (Parsons & Rizzo, 2008c), which was developed for attention assessment are also used with different clinical disorders, such as posttraumatic stress disorders (Wiederhold & Wiederhold, 2008) and traumatic brain injuries (Parsons et al., 2011).

Summary of this section

In was exposed that VR elicits real-life situations that are not always accessible in traditional assessment (Schultheis & Rizzo, 2001). This technology provides options that are not typically possible in traditional neuropsychology (Gould et al., 2007; Makam et al., 2004; Matheis et al., 2007; Phelps et al., 2004). Virtual reality proved to be versatile with various populations. It also provides control over all the aspects of the experiment while combining the reliability and fidelity of traditional assessment (Lalonde et al., 2013; Rizzo et al., 2004). Its use in the assessment of impulsivity seems promising.

Objectives of this thesis

In summary, impulsivity is an important factor in psychology and psychiatry, but is still ill-defined. Virtual reality is thought to address the shortcomings of traditional cognitive assessments (for a discussion, see Parsons et al., 2015). It is believed to be a powerful tool for both assessment and intervention (Riva, 2005). Virtual reality allows reproducing real-life settings under controlled conditions where the participant is expected to react similar to how he would in real-life settings. That is, standardized laboratory conditions are here paired with believable situations that mimic real-life events (Wilson, Foreman et al., 1997). Additionally, VR allows to precisely record all participant responses. With the help of a visor or other tracking technology, it also allows the participant to interact with the environment. This interaction increases the participant's perception that the virtual representation is real. This phenomenon, called sense of presence, is associated with performances that have a high predictive validity (IJsselsteijn et al., 2000; Kalawsky, 2000; Riva, Davide et al., 2003; Sanchez-Vives & Slater, 2005).

As outlined above, current methods to assess impulsivity are limited. The main objective of this thesis is to develop a novel task to assess impulsivity in a broader spectrum than what is current done with available tasks. As VR seems able to address many of the limitations of current assessments, the use of this technology appears promising for such a goal. It is hypothesized that VR should have a better predictive ability than traditional tasks. This is a perspective that is recently also supported by other publications (Armstrong et al., 2013; Henry et al., 2013; Henry, Nolin, Drouin-Germain, et al., 2011; Henry, Nolin, & Joyal, 2011; Nolin & Boucher, 2011; Nolin, Stipanicic et al., 2013; Nolin et al., 2012; Parsons et al., 2011, 2015). To meet these objectives, the following sections are comprised of three articles (Chapters 2 to 4).

The first article (Chapter 2) aims at proposing a conceptual and operational definition of impulsivity. The current definitions of impulsivity will be outlined as well as current assessments. The available neuropsychological tests will be detailed to help researchers and clinicians in their assessment choices of impulsivity in regards of the definition proposed.

The following chapter (Chapter 3) will then take one the most popular cognitive inhibition task, the Stroop, and put it in a Vre for adults. The objectives of this experiment are 1) to explore if the VR-Stroop proposed in this thesis is able to assess multiple components of impulsivity simultaneously; 2) to verify if the task was able to elicit a Stroop-effect; and 3) to study task parameters.

The fourth chapter consist of another experiment also using the VR-Stroop, this time with adolescents. The main objectives with this experiment are 1) to compare the performances on the virtual Stroop and the traditional task; and 2) to explore the task's validity and sensitivity. It is hypothesized that the virtual task would show similar properties than the paper-pencil task. A last objective of this experiment is to explore the ecological value of this task. To do so, predictive abilities of the VR task were compared to the traditional task. Both tasks are compared in their abilities to predict impulsivity with an ecological assessment of behaviours.

In Chapter 5, a general and specific discussion will then follow. Strenghts and weaknesses of the current thesis will be explored. Also, suggestions for future research will be provided.

Chapter 2
Évaluation clinique de l'impulsivité

Titre : Évaluation clinique de l'impulsivité

Title: Clinical assessment of impulsivity

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ÉVALUATION CLINIQUE DE L'IMPULSIVITÉ

CLINICAL ASSESSMENT OF IMPULSIVITY

Résumé

Bien que l'évaluation du potentiel impulsif d'une personne soit couramment exigée en milieu clinique, il s'agit d'une tâche difficile pour laquelle peu d'instruments existent. L'impulsivité est un construit multidimensionnel dont les principales composantes nécessitent des instruments de mesure spécifiques. La grande majorité des études et des milieux cliniques utilisent un seul outil (p. ex., mesure d'un état ponctuel) ou des approches mal adaptées aux clientèles psychiatriques ou judiciaires (p. ex., questionnaires autorapportés). Le but ici est de proposer au lecteur une définition conceptuelle et opérationnelle de l'impulsivité, ainsi qu'une description exhaustive et critique des instruments de mesure disponibles pour évaluer chacun de ses aspects.

Mots clés : impulsivité, évaluation, mesures, neuropsychologie, psychiatrie.

Abstract

Although the assessment of a person's potential for impulsivity is commonly required in clinical settings, it remains a challenging task for which few instruments exist. Impulsiveness is a multidimensional construct with principal components requiring specific measuring instruments. The great majority of existing studies and clinical settings use only one tool (e.g. measure of a specific state) or approaches poorly adapted to psychiatric or legal clienteles (e.g. self-reported questionnaires). The goal of this article is to propose a conceptual and operational definition of impulsivity, as well as an exhaustive and critical description of the measuring instruments available to evaluate each one of its aspects.

Key words: impulsivity, assessment, instruments, neuropsychology, psychiatry.

INTRODUCTION

Étant donné que l'impulsivité est l'un des symptômes les plus communs du DSM-5 (APA, 2013), on demande fréquemment au clinicien de l'évaluer. Cependant, les mesures validées et disponibles sont souvent basées sur la présence de comportements antérieurs ou de questionnaires adressés à la personne. Il est préférable d'obtenir une évaluation directe, comportementale, de l'impulsivité, surtout en psychiatrie, ce qui n'est pas toujours aisé à faire. D'une part, l'impulsivité est une entité clinique multidimensionnelle complexe, fluctuant dans le temps. D'autre part, les instruments valides et accessibles, mesurant directement ses différentes composantes, sont relativement peu nombreux. Les revues de la documentation concernant la mesure de l'impulsivité sont rares et celles disponibles sont incomplètes (Matusiewicz & Lejuez, 2012; Parker & Bagby, 1997) ou centrées sur des logiciels commercialisés par leurs auteurs (Dougherty, Mathias, Marsh, & Jagar, 2005; Mathias, Marsh- Richard, & Dougherty, 2008).

L'importance de mesurer l'impulsivité en psychologie ou psychiatrie légale est encore plus grande, étant donné le lien étroit entre l'impulsivité et le risque de commissions d'actes violents (Douglas & Webster, 1999; Hollander & Stein, 1995). D'ailleurs, l'impulsivité est au cœur des psychopathologies associées à la violence, comme les troubles de personnalité antisociale et borderline, les troubles d'abus de substances psychoactives, le trouble des conduites, le trouble explosif intermittent, le trouble bipolaire et le trouble déficitaire de l'attention avec hyperactivité (Grant & Potenza, 2011). C'est pourquoi l'importance de mesurer l'impulsivité en milieu médico-légal (en particulier de manière directe, comportementale) est soulignée depuis longtemps (Cherek, Moeller, Dougherty, & Rhoades, 1997; Dolan & Fullam, 2004; White, Moffitt, Caspi, Bartusch, Needles, & Stouthamer-Loeber, 1994).

Le but de cet article est de faire une recension plus complète et objective des façons d'évaluer les différents types d'impulsivité. Ces évaluations devraient permettre de mieux déterminer qui, parmi un groupe de personnes données, est à risque élevé de commettre des actes impulsifs.

Les sous-types d'impulsivité

L'impulsivité est une entité clinique complexe, multifactorielle et divisible en plusieurs sous-types (Evenden, 1999). Quelques auteurs distinguent l'impulsivité fonctionnelle (adaptée, comme réagir rapidement en cas d'urgence) de l'impulsivité dysfonctionnelle (Caci, Nadalet, Baylé, Robert, & Boyer, 2003; Dickman, 1990). Cependant, dans le but de ne pas confondre impulsivité et promptitude (ou efficacité), nous considérerons essentiellement la connotation négative de l'impulsivité. Les analyses factorielles identifient généralement de 3 à 4 composantes principales de l'impulsivité dysfonctionnelle. Les typologies les plus connues sont les suivantes : a) la motrice, l'attentionnelle ou cognitive et la non planifiée (Patton, Stanford, & Barratt, 1995); b) la trop grande spontanéité, l'absence de persévérance et l'insouciance (Gerbing, Ahadi, & Patton, 1987); c) la précipitation, le défaut de préméditation, le manque de persévérance et la recherche de sensation (Whiteside & Lynam, 2001); d) la trop grande vitesse d'exécution, la faible inhibition d'une réponse et l'inconsidération pour les conséquences futures (Dougherty, Mathias, Marsh-Richard, Furr, Nouvion, & Dawes, 2009). Une autre distinction importante est celle entre le trait (stable) et l'état (ponctuel) impulsif. Le trait impulsif réfère à des caractéristiques de la personnalité (Eysenck & Eysenck, 1978), tandis que l'état impulsif est plus circonstanciel et spécifique à une situation donnée (Moeller, Barratt, Dougherty, Schmitz, & Swann, 2001). L'impulsivité dite de trait influence négativement le fonctionnement exécutif (planification, organisation, raisonnement, inhibition et flexibilité) et compromet l'habileté à maintenir un certain rythme dans le traitement de l'information (Hollander & Stein, 1995). Elle ne se manifeste pas nécessairement au sein d'une modalité donnée (motrice, attentionnelle ou cognitive). Elle affecte plutôt le fonctionnement global de l'individu (Leshem & Glicksohn, 2007). Il s'agit d'une prédisposition, relativement stable, généralement liée à la recherche de sensations ou de nouveautés (Webster & Jackson, 1997). Elle traduit soit un manque de considération pour les conséquences futures, soit une insouciance par rapport à celles-ci (ou les deux). Étant stable dans le temps, le trait impulsif peut être décelé à l'aide d'échelles de mesure autorapportées (de préférence auprès de populations non cliniques; Stanford. Mathias, Dougherty, Lake, Anderson, & Patton, 2009), tel que décrit plus loin. Ceci n'est pas le cas de l'état, que l'on doit mesurer à l'aide de tests comportementaux directs (Dougherty et al., 2005). L'état impulsif, passager ou fluctuant, s'exprime en présence d'un contexte spécifique. À noter que ce contexte n'est pas nécessairement négatif (une forte émotion positive par ex., Cyders & Smith, 2008). Ce sont les conséquences du comportement qui le sont généralement.

Une bonne définition de l'impulsivité est celle proposée par Moeller et ses collègues (2001). Elle incorpore plusieurs composantes et souligne ses effets néfastes pour la personne impulsive et son entourage. Il s'agit d'« une prédisposition à réagir rapidement et sans planification à des stimuli internes ou externes, sans égard aux conséquences possibles pour l'individu impulsif ou les autres » [traduction libre] (p. 1784).

Il devient donc extrêmement difficile d'évaluer l'impulsivité à l'aide d'une mesure unique. Il s'agit plutôt de choisir les meilleures épreuves en fonction de la ou des composantes à évaluer. Ces composantes distinguent des sous-types d'impulsivité que l'on peut résumer ainsi :

1) Impulsivité motrice (trop grande spontanéité, précipitation ou vitesse d'exécution exagérée).
2) Faible capacité d'arrêt (difficultés à empêcher la commission d'un geste déclenché).
3) Impulsivité attentionnelle, impulsivité cognitive ou manque de persévérance (déficit d'attention; grande sensibilité à l'interférence interne ou externe, vigilance précaire).
4) Gratification immédiate (évitement des délais).
5) Recherche de sensations, prise de risque, insouciance et insensibilité pour les conséquences (je-m'en-foutisme et non-planification).

PRINCIPALES MESURES D'IMPULSIVITÉ POUR ADULTES

L'évaluation de l'impulsivité ou de son potentiel peut se faire à plusieurs niveaux : génétique (p. ex., le gène MAOA), endophénotypique (p. ex., systèmes sérotoninergiques, circuits d'activations cérébrales, patrons d'ondes corticales), phénotypique (p. ex., neuropsychologie, comportements, questionnaires). C'est de ce dernier niveau qu'il sera question ici. Les deux grandes classes de mesures phénotypiques sont les questionnaires et les évaluations neuropsychologiques. Les premiers servent surtout à évaluer les traits impulsifs, alors que les secondes permettent d'évaluer tant l'état (mesure ponctuelle), que les traits (par l'entremise de mesures répétées afin de documenter l'impulsivité de trait). L'utilisation de questionnaires, approche classique, comporte plusieurs inconvénients, car toutes les données sont basées sur la mémoire, la compréhension, la collaboration et la motivation de la personne interviewée. Ainsi, la valeur des conclusions tirées de questionnaires utilisés en milieu psychiatrique est souvent faible, a fortiori en milieu médico-légal. Néanmoins, comme les questionnaires sont très largement utilisés pour évaluer l'impulsivité et comme ils permettent des évaluations rapides (et de groupes), ils seront brièvement décrits ci-après. Les mesures neuropsychologiques directes seront exposées par la suite.

Les questionnaires

Les questionnaires s'adressent généralement au répondant directement, mais on peut également interroger un proche, un collègue ou un ami de la personne. Voici les plus utilisés.

Le *questionnaire I_7 (Impulsiveness questionnaire: Impulsiveness, Venturesomeness and Empathy)* (Eysenck, Pearson, Easting, & Allsopp, 1985). Durant les années 1980, le I_7 comptait parmi les questionnaires les plus utilisés pour évaluer les traits impulsifs chez l'adulte. Il est issu de la conceptualisation orthogonale de la théorie de la personnalité d'Eysenck et Eysenck (1978). Il contient 54 questions avec des réponses limitées à « vrai » ou « faux ». Les items visent l'évaluation de trois principaux facteurs, soit la tendance à agir sous l'impulsion (*impulsiveness*), la propension à rechercher les sensations fortes (*venturesomeness*) et le manque d'empathie. Un avantage de cette mesure est qu'elle comporte un aspect supplémentaire permettant d'évaluer la désirabilité sociale par l'entremise de l'empathie et de la sensibilité à autrui. Cet avantage est considérable puisque le jugement et l'introspection des personnes impulsives, surtout en milieu carcéral, peuvent être déficients. Le score de cette échelle corrèle fortement avec celui d'une autre échelle, construite spécifiquement pour évaluer l'impulsivité, la *Barratt Impulsiveness Scale* (BIS-11) (Patton et al., 1995), si bien que cette dernière l'a peu à peu remplacée.

Le *questionnaire BIS version 11.* Le *BIS-11* reste la mesure d'impulsivité la plus utilisée aujourd'hui et le modèle sur lequel elle est basée (trois composantes principales de l'impulsivité : motrice, attentionnelle et non planifiée) a servi d'assises théoriques et méthodologiques à de nombreuses études (Stanford et al., 2009). Initialement développée en 1959, la version 11 contient 30 items sur une échelle de Likert (1 à 4) qui permettent d'évaluer de multiples facettes de l'impulsivité, dont l'attention, l'impulsivité motrice, l'autocontrôle (planification et réflexion), la complexité cognitive (appréciation des tâches réflexives), la persévérance (stabilité du mode de vie) et l'instabilité cognitive (fuite des idées). Malgré sa grande popularité, l'utilisation du *BIS-11* est déconseillée en milieu psychiatrique ou légal, car les réponses sont autorapportées (donc moins fiables; p. ex., « je réfléchis soigneusement »; « je me concentre facilement ») et ses items ne sont pas adaptés à ces milieux (« je planifie mes voyages à l'avance », « je change souvent de travail », « je me sens agité lors de spectacles », etc.). Bien entendu, des gens recrutés en psychiatrie ou en milieu carcéral obtiendront des résultats significativement différents de ceux de la population générale (Enticott, Ogloff, Bradshaw, & Fitzgerald, 2008; Patton et al., 1995; Swann, Anderson, Dougherty, & Moeller, 2001). Toutefois, cette échelle n'a pas de valeur prédictive pour la commission de gestes impulsifs ou agressifs en milieu médico-légal (Cornélis, Joyal, Dubreucq, & Côté, 2012; McDermott, Edend, Quanbeck, Busse, & Scott, 2008). D'ailleurs, la structure factorielle de l'échelle lorsqu'elle est utilisée en milieu psychiatrique ou carcéral ne peut être confirmée (Haden & Shiva, 2008; Ireland & Archer, 2008; Ruiz, Skeem, Poythress, Douglas, & Lilienfeld, 2010). Son usage est donc préférable au sein de la population générale. À noter que la version 10 et non 11 est validée en français (Baylé et al., 2000).

Le *questionnaire UPPS (Urgency, Premeditation, Perseveration, Sensation)* (Whiteside & Lynam, 2001). Cette échelle relativement nouvelle a également été construite expressément pour évaluer l'impulsivité parmi la population générale. Elle est validée en français (Van der Linden et al., 2006). Comme son nom l'indique, elle permet l'évaluation de 4 composantes de l'impulsivité : la précipitation (*urgency*), le défaut de préméditation (*premeditation*), le manque de persévérance (*perseveration*) et la recherche de sensation (*sensation*). La première composante, précipitation, réfère à des comportements émis de façon précipitée, sans réflexion adéquate au préalable (impulsivité motrice). Notons que ces réponses promptes sont exacerbées par des émotions fortes, tant négatives que positives (Cyders & Smith, 2008). Le manque de persévérance est davantage associé à des capacités attentionnelles (attention soutenue en particulier; difficultés à rester concentré sur une tâche et à ignorer des stimuli distrayants non pertinents). Le défaut de préméditation est quant à lui associé à des dysfonctions exécutives (fonctions cognitives supérieures; la personne planifie mal ses actions et n'anticipe pas leurs conséquences). Enfin, la recherche de sensations fortes est associée à des caractéristiques de la personnalité ou du tempérament rappelant l'échelle de Zuckerman présentée plus loin. Cette facette est également postulée par la théorie classique de la personnalité d'Eysenck et Eysenck (1969). Un individu peut prendre des risques ou s'engager dans des activités dangereuses (p. ex., sports extrêmes, promiscuité sexuelle), mais il peut aussi être en constante recherche de nouvelles expériences ou de défis quotidiens (p. ex., changer fréquemment d'emploi ou de domicile).

D'autres questionnaires d'impulsivité pour adultes (autorapportés ou à l'intention des proches) ont été construits, mais ils servent surtout à confirmer la présence d'un trouble déficitaire de l'attention avec ou sans Hyperactivité (TDA/H adulte). Ces échelles (L'*Inventaire des symptômes du TDAH*, l'*Échelle d'autoévaluation du trouble déficitaire de l'attention avec/sans hyperactivité chez l'adulte*, l'*Adult ADHD Self-Report Scale*, l'*Échelle d'évaluation de Wender-Utah* ou le *Weiss Functional Impairment Rating Scale*) sont accessibles gratuitement en version française (www.attentiondeficit-info.com) ou anglaise (www.caddra.ca). D'autres échelles commerciales sont également disponibles : l'*Adult Self-Report* et l'*Adult Behavior Checklist* d'Achenbach, Psychological Assessment Resources Inc et les *Conners Adult ADHD Rating Scales*, Pearson Assessments, en versions française et anglaise. Un autre questionnaire très utilisé, notamment pour évaluer les comportements extériorisés et l'impulsivité est le *Child Behavior Checklist* (*CBCL*; Achenbach & Edelbrock, 1983; Achenbach & Rescorla, 2001). Cependant, comme son nom l'indique, ce questionnaire concerne les enfants et non les adultes. Le clinicien intéressé à faire le pont entre les comportements en bas âge et leurs manifestations et répercussions à l'âge adulte est invité à consulter l'*Entretien diagnostique pour le TDAH chez l'adulte* (*DIVA 2.0*, Kooij & Francken, 2010). Cette échelle est basée sur la conception diagnostique du trouble d'attention tel qu'émis par le *DSM-IV-TR* (APA, 2000).

Finalement, un autre questionnaire classique et très populaire pour évaluer l'impulsivité est la *Sensation Seeking Scale* (*SSS*) de Zuckermann (1979), toutefois, il sert plutôt à évaluer une facette particulière de l'impulsivité, soit la tendance à vouloir vivre des sensations fortes. Cette tendance a été définie comme «un besoin d'expérimenter diverses sensations et une propension à prendre des risques physiques et sociaux pour combler ce besoin » (Zuckerman, 1979). La *SSS* a été bâtie pour évaluer ce trait et ses items forment quatre composantes principales : 1) recherche de sensations et d'aventures; 2) recherche d'expériences nouvelles;

3) désinhibition sociale; 4) propension à l'ennui. Cette échelle est donc très utile pour évaluer la tendance à la recherche de sensations, mais, comme pour les autres mesures autorapportées, elle dépend fortement de la collaboration et de l'honnêteté du répondant. Cette échelle a été validée en français (Loas et al., 2001).

Afin d'effectuer des évaluations plus objectives, plus difficiles à biaiser et mieux adaptées à des populations non générales, il convient d'utiliser des paradigmes comportementaux, souvent issus de la neuropsychologie. Ces paradigmes, disponibles en format papier-crayon (plus vieux) ou informatisés (plus précis), sont décrits ci-après.

Les mesures comportementales directes non informatisées

Tracer une ligne le plus lentement possible. Cette épreuve aisée à comprendre et à exécuter a été développée dans le but d'évaluer l'impulsivité motrice chez l'enfant, quel que soit son niveau de développement ou d'intelligence (Maccoby, Dowley, Hagen, & Degerman, 1965). La validité de la tâche a été démontrée auprès d'enfants de niveau préscolaire hyperactifs (Schleifer, Weiss, Cohen, Elman, Cvejic, & Kruger, 1975). Elle peut également être utilisée chez l'adulte, notamment auprès de populations défavorisées ou psychiatriques (p. ex., Rohrbeck & Twentyman, 1986). Il s'agit pour le participant de simplement tracer une ligne à l'aide d'un crayon, de haut en bas d'une feuille de papier, à l'intérieur d'une colonne, sans toucher ses côtés, le plus lentement possible. Le nombre de bris de consigne et de secondes pour réaliser la tâche représente les variables dépendantes.

Tracer un cercle le plus lentement possible. Épreuve qui rappelle celle du tracé d'une ligne, où le participant doit suivre avec un crayon le tracé d'un cercle apparaissant sur une feuille. Il doit ensuite le refaire le plus lentement possible. La différence de temps consacré à l'exécution des deux cercles représente la principale variable dépendante (moins elle est élevée, plus la personne est impulsive) (Bachorowski & Newman, 1985). Cette tâche motrice, non verbale, est surtout utilisée auprès d'enfants, mais elle peut aussi bien servir chez l'adulte (Wingrove & Bond, 1997).

Les tâches de labyrinthes. Les tâches papier-crayon classiques de type labyrinthes (Porteus, 1959) ou *Trail-Making A et B* (*Army Individual Test Battery*, 1944; Reitan, 1958) ont été originellement développées pour mesurer rapidement certaines fonctions exécutives supérieures («les processus du choix, d'essai, de rejet et de sélection d'options comportementales ou cognitives » [traduction libre] (Porteus, 1959, p. 7). Il s'agit pour le participant de tracer un chemin dans un labyrinthe (Porteus) ou de relier des points (*Trail-Making*) dessinés sur papier le plus rapidement possible, sans lever son crayon et en évitant les erreurs (p. ex., entrer dans une impasse ou relier les points en désordre numérique ou alphanumérique). Il s'avère cependant que plusieurs aspects de l'exécution de ces tâches peuvent servir à évaluer l'impulsivité motrice (Helmers, Young, & Pihl, 1995), tant chez les personnes limitées intellectuellement (Gow & Ward, 1982), les enfants (Kindlon, Mezzacappa, & Earls, 1995), les délinquants (White et al., 1994), que les personnes âgées atteintes de démence (p. ex., Amieva et al., 1998). En particulier, le nombre de fois où la personne franchit les murs du labyrinthe, le nombre de fois où elle soulève son crayon, le nombre de fois où elle s'aventure dans une impasse (labyrinthe), le ratio entre le score total et le temps requis pour accomplir la tâche (*Trail Making*; un temps très bas étant souvent associé à un haut taux d'erreur), le nombre de fois où elle ne suit pas l'ordre numérique (*Trail Making A*) ou l'alternance alphanumérique (*Trail-Making B*) représentent toutes des variables pouvant estimer le potentiel impulsif d'une personne.

Estimation du temps. Étant donné que les gens impulsifs ont tendance à surestimer la vitesse de passage du temps, plusieurs études ont utilisé des épreuves d'estimation du temps pour évaluer le potentiel impulsif, en particulier chez le délinquant (Davids & Falkof, 1975;

Siegman, 1961; White et al., 1994). À l'aide d'un chronomètre ou d'une montre, il s'agit simplement de demander au participant d'estimer le nombre de secondes qui s'écoulent entre deux signaux dont l'étendue varie d'un essai à l'autre (p. ex., 5, 15 et 30 secondes). Par la suite, la personne doit produire d'elle-même les deux signaux représentant ce qu'elle estime être un laps de temps donné (p. ex., 5, 15 et 30 secondes). Les personnes impulsives ont une forte tendance à surestimer les intervalles de temps (subjectivement plus lentes pour elles).

Le paradigme du Go/no-go de Luria. La façon classique d'évaluer l'impulsivité motrice est l'utilisation d'un paradigme de *Go/no-go*, mis de l'avant par Luria (1966). Ce paradigme exige du sujet qu'il réponde le plus rapidement possible à un stimulus émis par l'expérimentateur (p. ex., imiter l'expérimentateur qui donne un bref coup de poing dans sa propre paume), sauf quand le stimulus diffère des autres (p. ex., l'expérimentateur donne deux brefs coups de poing dans sa paume), auquel cas le sujet doit inhiber sa réponse. Cette mesure simple est très sensible à l'impulsivité motrice et aux lésions frontales; elle peut d'ailleurs être administrée à tout endroit (p. ex., au chevet du patient) (Dubois, Slachevsky, Litvan, & Pillon, 2000). Cependant, comme elle n'est pas informatisée, il est plus difficile de compiler le score du participant et d'uniformiser les administrations d'une fois à l'autre ou d'une personne à l'autre. Nous verrons plus loin des versions informatisées et virtuelles de ce paradigme classique.

Le test de Stroop. L'effet conflictuel de Stroop est aussi bien connu, mais son test est plutôt associé à l'inhibition attentionnelle (contrôle de l'interférence) qu'à l'inhibition motrice (Stroop, 1935). L'effet Stroop se manifeste par une augmentation significative des temps de réaction verbale lorsqu'on doit énoncer la couleur d'un mot écrit avec des lettres dont la couleur est différente de celle que le mot désigne (p. ex., dire vert pour le mot « rouge » écrit en vert). Il est plus facile (rapide) d'énoncer la couleur d'un mot désignant la même couleur que celle avec laquelle il est écrit (le mot « rouge » écrit en rouge). Cet effet est aisément observable, en particulier chez l'adulte (l'expérience de lecture, plus grande, a atteint un niveau de quasi-réflexe), non daltonien, non analphabète, pour des mots tirés de sa langue maternelle. Cette tâche sert à plusieurs fins, mais cette condition d'interférence requiert une bonne capacité d'inhibition cognitive, de concentration et de mémoire de travail (Lezak, Howieson, Bigler, & Tranel, 2012). Contrairement aux épreuves de tracés décrites plus haut, aucune réponse manuelle n'est impliquée ici, ce qui est utile lorsque le participant souffre de problèmes moteurs.

Les commandes motrices de Luria. Lorsque des participants présentent des difficultés de lecture, d'expression verbale ou ont un jeune âge (moins de 16 ans), il est possible d'évaluer leur inhibition attentionnelle (sensibilité à l'interférence) de façon motrice grâce au test des commandes motrices de Luria (1966). Il s'agit pour le participant d'exécuter un mouvement opposé à celui émis par l'expérimentateur, par exemple donner un coup sur la table lorsqu'on en donne deux et deux coups lorsqu'on en donne un (Dubois, et al., 2000). Ce test neurologique classique permet d'évaluer l'inhibition attentionnelle, la concentration et la mémoire de travail (Lezak, et al., 2012).

Les tests de Tours. Les évaluations neuropsychologiques basées sur l'utilisation de tours (*tour de Londres, tour de Hanoi, tour de Toronto*, etc.) servent avant tout à évaluer les capacités de planification et de résolution de problèmes, mais elles sont très sensibles à l'impulsivité motrice et attentionnelle, car elles nécessitent de la réflexion et de la manipulation motrice (voir Lezak et al., 2012 pour une description de ces tests). Les tours exigent de l'analyse, de la planification et des déplacements de pièces tout en respectant des règles strictes, tous des éléments susceptibles d'être affectés par de l'impulsivité (Luciana, Collins, Olson, & Schissel, 2009). L'impulsivité motrice est associée à une initiation des mouvements trop rapide et, des bris de consignes. Le manque de planification ou l'inattention subséquente entrainent un nombre excédentaire de déplacements et une perte de temps considérable lors de l'exécution (approche par essais-erreurs ou retours en arrière). D'autres signes comme des déplacements trop rapides ou l'attrait pour des stimuli saillants sont également d'excellents indicateurs d'impulsivité.

Le test de Hayling. Finalement, le test de Hayling (Burgess & Shallice, 1996) permet d'évaluer un type d'impulsivité plus cognitif. Il s'agit d'énoncer des phrases simples incomplètes (il manque le dernier mot), que le participant doit compléter (p. ex., elle est allée se faire couper les cheveux chez la....). Le sujet doit dire le premier mot qui lui vient à l'esprit (mesure de base), ce qui est aisé puisque la probabilité d'occurrence des mots est très élevée (p. ex., coiffeuse). Cependant, lors de la seconde phase du test, le sujet doit au contraire dire un mot qui n'a rien à voir avec le contexte. Cette condition est sensible à l'impulsivité et aux lésions frontales (Burgess & Shallice, 1996). Fait intéressant, la condition d'inhibition sollicite des régions frontales corticales inférieures et le cortex cingulaire antérieur, comme les autres tâches d'impulsivité (p. ex., Horn, Dolan, Elliott, Deakin & Woodruff, 2003, voir plus bas), mais surtout à gauche (Collette, Van der Linden, Delfiore, Degueldre, Luxen, & Salmon, 2001; Nathaniel-James, Fletcher, & Frith, 1997). Ceci reflète peut-être la nature plus cognitive ou verbale de la tâche.

Bien que ces mesures d'impulsivité non informatisées soient très accessibles (elles ne coûtent presque rien, nécessitent peu de formation et sont faciles à comprendre) et pratiques (elles peuvent s'effectuer partout), elles ne permettent pas d'évaluations uniformes d'une fois à l'autre (faible fidélité). De plus, l'examinateur ne peut, seul, prendre en compte plusieurs variables importantes de l'impulsivité motrice et attentionnelle, telles que le temps de réaction moyen, la variation des temps de réaction, la moyenne des omissions et des commissions et la baisse de vigilance. Avec l'accessibilité croissante des ordinateurs de table, ordinateurs portables, tablettes électroniques, téléphones intelligents, Internet haute vitesse et autres technologies informatiques, un nombre croissant de tests informatisés d'impulsivité ont été développés.

Les mesures comportementales directes informatisées

a) L'impulsivité motrice et les paradigmes Go/no-go. La majorité des mesures directes d'impulsivité pour adultes sont informatisées et basées sur le protocole de *Go/no-go*. Dans le cadre des versions informatisées de ce paradigme, la personne évaluée doit appuyer sur une touche reliée à un ordinateur le plus rapidement possible en réaction à l'apparition d'un stimulus à l'écran (ou sonore; temps de réaction simple). Cependant, elle doit retenir son geste lors de l'apparition d'un stimulus différent d'occurrence moindre (généralement 20 % à 25 % des essais), de même modalité sensorielle ou non (auditif ou visuel). Ce type de protocole est très utilisé pour évaluer l'impulsivité motrice, tant parmi la population générale que clinique (p. ex., Drewe, 1975), et sa bonne exécution est associée à l'activation de plusieurs aires corticales et sous-corticales impliquant plus particulièrement les régions préfrontales ventromédianes (Horn, et al., 2003), justement liées à l'inhibition comportementale (Stuss & Knight, 2013). Le go/no-go informatisé est donc largement utilisé dans le milieu médico-légal (Dolan & Fullam, 2004; Mathias, et al., 2008). Nous avons par exemple démontré qu'il permet de distinguer parmi des meurtriers atteints de troubles mentaux sévères, ceux qui reçoivent des diagnostics concomitants (troubles de personnalité et d'abus de substance psychoactive), des autres (Joyal et al., 2007). Le problème avec ce type de protocole est qu'il a une faible sensibilité pour les manifestations plus subtiles d'impulsivité, ainsi qu'une faible valeur prédictive (l'état qu'il mesure est très fluctuant; Cornelis et al., 2012). Des mesures plus fines devront donc être développées, notamment à l'aide de la réalité virtuelle. Néanmoins, concernant leur utilité en milieux psychiatrique et judiciaire, les principaux protocoles de type Go/no-go sont décrits ci-dessous.

Le Test Of Variables of Attention (T.O.V.A.). Le T.O.V.A. est une épreuve aisée à comprendre et à compléter, basée sur le paradigme du Go/no-go. Cette tâche permet d'évaluer l'impulsivité motrice, l'inattention et la vigilance d'enfants et d'adultes (Greenberg & Waldmant, 1993). Cependant, ce test est utilisé surtout pour confirmer le diagnostic de TDAH (Forbes, 1998; www.tovatest.com). Les stimuli sont non verbaux, visuels (carrés placés à différents endroits de l'écran) ou auditifs (simples sons).

Ce logiciel fonctionne avec un bouton pressoir spécifique, ce qui lui permet de fournir des mesures de temps de réaction très précises (de l'ordre de 1 ms, alors que l'utilisation d'un clavier ou d'une souris d'ordinateur peut générer des variations erronées de mesure pouvant atteindre 28 ms). Le logiciel est basé sur des données normatives, mais elles sont issues d'enfants provenant de la banlieue de Minneapolis (et non de milieux urbains moins favorisés) et d'adultes recrutés pour la plupart dans des universités, tous caucasiens à 99 % (Leark, Greenberg, Kindschi, Dupuy, & Hughes, 2007). En outre, la tâche est extrêmement fastidieuse et ennuyante, nécessitant 21 minutes pour être accomplie (ceci est délibéré, étant donné la volonté de mesurer la vigilance). Le *Continuous Performance Test* (*CPT*), décrit ci-après, est plus couramment utilisé comme mesure d'impulsivité.

Le Continuous Performance Test (CPT). Il existe plusieurs versions de ce paradigme, développé par Rosvold, Mirsky, Sarason, Bransome Jr, et Beck (1956) pour évaluer les séquelles de l'épilepsie. Déjà, à l'époque, il y avait deux versions soit la X (peser sur un bouton le plus rapidement possible lors de la présentation d'une lettre de l'alphabet à l'exception du X) et la A-X (plus complexe; peser sur un bouton le plus rapidement possible lors de la présentation d'une lettre de l'alphabet à l'exception du X, mais seulement lorsque précédé immédiatement du A, ce qui implique la mémoire de travail). Ces paradigmes ont été repris par plusieurs auteurs, le plus connu étant Conners, qui l'a utilisé pour évaluer les effets de psychostimulants sur l'attention (Conners, Eisenberg, & Barcai, 1967), pour ensuite le commercialiser comme outil diagnostique pour le TDAH (CPT-II, avec données normatives) (Conners & Staff, 2000). Comme le *T.O.V.A.*, le *CPT-II* permet d'évaluer l'impulsivité motrice (erreurs de commission), l'inattention (erreurs d'omission), la stabilité des réponses (variabilité des temps de réaction et des bonnes réponses dans le temps), l'effort fourni (p. ex., taux d'omissions élevés malgré de bons temps de réaction) et la vigilance (baisse significative des réponses dans le temps). Cependant, la qualité de ses données normatives est supérieure à celle du *T.O.V.A.*, étant basées sur près de 2000 personnes de 6 ans ou plus provenant de la population générale (Conners & Staff, 2000; Conners, Epstein, Angold, & Klaric, 2003). Il s'effectue aussi plus rapidement, soit en 14 minutes.

Une autre version, le *CPT-IP* (*Identical Pairs*), a été développée pour solliciter davantage la mémoire de travail tout en étant accessible aux personnes atteintes d'un trouble mental sévère (Cornblatt, Lenzenweger, & Erlenmeyer-Kimling, 1989; Cornblatt, Risch, Faris, Friedman, & Erlenmeyer-Kimling, 1988). Cette tâche permet également une évaluation plus complète de l'attention et de l'impulsivité (Dougherty, Marsh, & Mathias, 2002). Dans cette version, le participant doit s'abstenir de peser sur le bouton lorsque deux lettres identiques apparaissent à l'écran (meilleure sollicitation de la mémoire de travail), mais les stimuli sont physiquement distincts (p. ex., W et C), ce qui facilite la tâche. Cette dernière a été incluse dans une batterie de tests neuropsychologiques à l'intention des gens atteints de schizophrénie (MATRICS, avec données normatives; Green, Kern, & Heaton, 2004; www.matricsinc.org).

Une autre version du *CPT-IP* contient une plus grande proportion d'essais avec des stimuli successifs semblables, mais non identiques (plus difficiles; 33 % des stimuli) et deux conditions mnésiques (*Immediate Memory Test/Delayed Memory Test*; Dougherthy et al., 2003; www.nrlc-group.net/software/software.php). Cette version est donc plus sensible et mieux adaptée à la population que les tests présentés ci-haut, conçus pour confirmer des diagnostics.

b) Impulsivité attentionnelle ou impulsivité cognitive et manque de persévérance. L'impulsivité de type attentionnelle (parfois appelée cognitive) s'observe par une grande sensibilité aux interférences, soit externes (stimuli de l'environnement), soit internes (la focalisation de la personne décroche de façon intermittente). Traditionnellement, la sensibilité aux interférences internes s'évalue par le test de Stroop, mentionné plus haut (et désormais offert en version logicielle) ou par le nombre d'omissions observées durant les tâches de type Go/no-go (déficit attentionnel). Peu de mesures neuropsychologiques pour adultes évaluent la sensibilité à l'interférence externe. Chez l'enfant, voir l'excellent *test de la Statue*, de la *batterie A Developmental NEuroPSYchological Assessment* (Korkman, Kirk, & Kemp, 2007). Les échelles de type Conners adultes servent, en revanche, à cette fin. Le manque de persévérance (ou trouble de la vigilance), quant à lui, ne peut s'observer qu'avec des tâches relativement longues et ennuyeuses, telles que le *CPT*, la *T.O.V.A.* ou une tâche d'attention soutenue comme Lottery du *Test of Everyday Attention* (*TEA*, McAnespie, 2001). Une tâche répétitive d'une durée d'au-delà de 10 minutes suffit généralement pour que la personne décroche pour de bon.

Une autre tâche classique d'impulsivité plutôt cognitive est celle d'appariements rapides de dessins similaires (*Matching Familiar Figure Test*, *MFFT*; Kagan, 1966), aujourd'hui administrée par ordinateur (Leshem & Glickson, 2007). Dans le cadre de cette tâche, le participant doit identifier le plus rapidement possible lequel de six dessins (ou images), présentés simultanément, est identique à un dessin cible. Bien entendu, chaque dessin est très semblable aux autres, ce qui exige un minimum de temps avant de trouver le bon stimulus. Le nombre d'erreurs et le temps de réaction représentent les principales variables dépendantes.

c) L'inhibition motrice et le paradigme Stop-Signal. Le paradigme Stop- Signal fait également partie de la famille Go/no-go, mais on mesure ici une entité clinique d'inhibition, en plus de l'impulsivité motrice (Logan & Cowan, 1984). L'indice d'arrêt est sonore (no-go; de faible fréquence, 25 % des essais), il précède le stimulus visuel (Go) et le temps de latence entre les deux présentations varie d'un essai à l'autre. Fait intéressant, le programme contient un algorithme qui s'adapte au temps de réaction moyen du participant dans le but qu'il commette 50 % d'erreurs (le participant presse la touche associée à l'indice Go malgré l'émission préalable du son dans environ 50 % des essais). Pour y parvenir, 50 ms sont soustraites (condition plus difficile) à la latence du prochain stimulus no-go lorsque la réponse est bonne (inhibition) et 50 ms sont additionnées (rendant la tâche plus aisée) à la suite de chaque essai échoué (commission). Le logiciel parvient ainsi à faire échouer à 50 % des tests en 64 essais, ce qui fait de cette mesure un test qui n'exige pas plus de temps à administrer que le *CPT-II*. Une fois la tâche complétée, le programme calcule non seulement les paramètres usuels des paradigmes Go/no-go (temps de réaction, nombre de commissions, nombre d'omissions, etc.), mais aussi l'estimation d'une variable théorique, le temps d'inhibition (Logan, Schachar, & Tannock, 1997). Plus le temps moyen requis entre la présentation du signal sonore et celle du stimulus visuel est élevé (temps de latence entre les deux présentations) pour qu'un participant inhibe effectivement sa réponse, moins le système inhibiteur de ce participant est efficace. La version Windows (nommée *Stop-it*; Verbruggen, Logan, & Stevens, 2008) d'un exécutable de cette tâche est disponible gratuitement (http://www.psy.vanderbilt.edu/faculty/logan/). Fait à noter, il semble que les tests CPT (impulsivité) et Stop-Signal (inhibition) ne sollicitent pas exactement les mêmes régions cérébrales (Swick, Ashley, & Turken, 2011), ce qui n'est pas sans rappeler les systèmes théoriques opposés de la motivation de Gray (Activation c. Inhibition; (Carver & White, 1994)).

d) Gratification immédiate (évitement des délais). L'immaturité développementale est associée à des prises de décisions désavantageuses pour l'individu, qui tend à choisir en fonction de l'attrait et de l'immédiateté au détriment du bénéfice à long terme (Logue, 1995).

L'épreuve des friandises. La première mesure connue des capacités d'attendre pour obtenir un meilleur gain est l'épreuve des friandises, utilisée chez l'enfant (Mischel & Ebbesen, 1970). Au cours de ce test, l'enfant a le choix de consommer tout de suite une friandise ou d'attendre une vingtaine de minutes, seul, pour en recevoir le double (ou plus; pour une vidéo du Marshmallow Test, voir : www.youtube.com/watch?v=4ZikfUI0G5o consulté la dernière fois le 5 aout 2015). Seulement le tiers des enfants de quatre ans réussissent ce test (Logue, 1995). Ils auront en moyenne de meilleurs résultats scolaires, un fonctionnement intellectuel plus élevé et un meilleur réseau social que les autres (Mischel, Shoda, & Peake, 1988). Ils gèrent aussi mieux leur stress et ont moins de problèmes comportementaux (Mischel, Shoda, & Rodriguez, 1989).

Gains monétaires. Chez l'adulte, des versions (informatisées ou non) offrant le choix entre de petits gains (ou de fortes probabilités de petits gains) monétaires immédiats et des sommes ultérieures plus intéressantes ont été développées pour évaluer la propension à éviter les délais et préférer la gratification immédiate (Kirby & Maraković, 1996; Reynolds & Schiffbauer, 2004). Une faible résistance à la tentation d'un petit profit à court terme aux dépens d'un meilleur gain à long terme est associée au TDAH (Solanto et al., 2001; Sonuga-Barke, Taylor, Sembi, & Smith, 1992), aux problèmes de dépendance (Bickel & Marsch, 2001), à la délinquance (Krueger, Caspi, Moffitt, White, & Stouthamer-Loeber, 1996), à la violence (Cherek et al., 1997) et à certains troubles extériorisés de la personnalité (borderline, antisociale et traits de psychopathie; Crean, de Wit, & Richards, 2000; Newman, Kosson, & Patterson, 1992). À remarquer que ces troubles sont souvent concomitants. Ils auraient notamment, l'évitement des délais et l'insouciance (ou l'ignorance) du futur comme point commun. À remarquer également que la capacité de résister à la gratification immédiate au profit d'un meilleur gain ultérieur est fortement corrélée à l'âge et à la maturité de la personne (Mischel et al., 1989).

e) Recherche de sensations, prise de risque, insouciance et insensibilité pour les conséquences (je-m'en-foutisme et non-planification). La recherche de sensations fortes, la tendance aux prises de risque et l'insouciance sont des facettes de l'impulsivité généralement liées à l'attirance pour la gratification immédiate, mais pas nécessairement à ses autres facettes, comme nous le verrons ici.

Le test de Rogers. Robert Rogers et ses collaborateurs ont développé une évaluation de la tendance à la prise de risque, de l'attrait pour l'attirance d'un stimulus et de l'apprentissage adaptée à l'imagerie cérébrale (Rogers et al., 1999a). Il s'agit pour le participant de choisir entre deux options, l'une ayant de fortes probabilités de rapporter un petit montant et l'autre de faibles probabilités de rapporter un gros montant. Des déficits d'apprentissage à cette tâche (tendance à choisir les gros montants malgré les pertes répétitives) sont associés à des lésions frontales ventromédianes, de faibles taux de sérotonine et des troubles de dépendance à des substances psychoactives illicites (Rogers et al., 1999b). Paulus, Rogalsky, Simmons, Feinstein et Stein (2003) ont développé une autre épreuve de prise de risque probabiliste (*Risky Gains Task*). Cependant, ces tâches n'ont pas de données normatives, elles ne sont pas disponibles commercialement et, conséquemment, sont peu utilisées à des fins cliniques.

La Iowa Gambling Task (IGT). L'IGT est le test neuropsychologique le plus utilisé pour évaluer la prise de risque et l'apprentissage (Bechara, 2007). Cette tâche a été développée pour être écologiquement valide (plus proche de la réalité) et évaluer la prise de décision chez des patients cérébrolés (Bechara, Damasio, Damasio, & Anderson, 1994). Il s'agit de simuler un contexte de prise de décisions dans des conditions de récompense, de punition et d'apprentissage, un peu comme un jeu de cartes. Au cours de la tâche (informatisée), l'individu doit piger, à 100 reprises, une carte provenant d'un de quatre paquets présentés (A, B, C ou D). Chaque pige entraine un gain ou une perte d'argent (2000 $ sont alloués au départ). Les paquets ne sont ni associés à la même probabilité, ni au même montant, de gains. Deux des paquets offrent de meilleures sommes, mais leurs probabilités de gains sont beaucoup plus petites, alors que leurs probabilités de pertes et l'importance de ces dernières sont plus grandes que celles des deux autres. Il s'agit donc d'un exercice d'apprentissage opérant (par essais-erreurs en tenant compte des conséquences) que des participants de la population apprennent rapidement : 25 essais en moyenne pour un apprentissage inconscient (favoriser les paquets avantageux sans savoir pourquoi) et 50 essais environ pour atteindre l'apprentissage conscient (comprendre la règle et pouvoir la verbaliser) (Bechara, Damasio, Tranel, & Damasio, 1997). Différentes variables dépendantes peuvent être mesurées (total des gains, nombre de cartes pigées dans les paquets optimaux ou non, vitesse de réaction, etc.), mais le ratio paquets avantageux/paquets désavantageux en blocs de 20 essais est particulièrement utile pour évaluer la progression du participant. Des données normatives sont disponibles pour chacune de ces variables (Bechara, 2007). En revanche, le problème majeur avec cette tâche est que sa validation de construit n'a pas été établie. Il est donc difficile de circonscrire ce qu'elle mesure (Buelow & Suhr, 2009; Matusiewicz & Lejuez, 2012). Néanmoins, quelques indices sont d'intérêt. Premièrement, des populations cliniques à fortes tendances impulsives et à la prise de risque ont des déficits marqués à l'IGT (particulièrement concernant les dépendances) (Bolla et al., 2003; Bolla, Eldreth, Matochik, & Cadet, 2005; Monterosso, Ehrman, Napier, O'Brien, & Childress, 2001). Deuxièmement, les résultats à l'IGT ne corrèlent pas (ou très faiblement) avec ceux des questionnaires (Monterosso et al., 2001; Stanford et al., 2009). Troisièmement, l'IGT ne semble pas associée aux mesures comportementales d'impulsivité motrice ou attentionnelle (McCloskey et al., 2009), alors qu'elle est fortement corrélée à la propension pour la gratification immédiate (Monterosso et al., 2001). Ces données font dire que la prise de risque, les mauvaises décisions, l'évitement des délais et la propension à la gratification immédiate sont des construits de l'impulsivité interreliés.

Le test du ballon (Balloon Analogue Risk Task, BART). Ce test sert aussi à évaluer la prise de risque, mais de façon beaucoup plus simple que l'IGT, sans grande implication des fonctions exécutives supérieures (Lejuez et al., 2002). Ceci offre la possibilité d'évaluer des personnes plus atteintes, déficientes intellectuellement ou atteintes de troubles psychotiques (Duva, Silverstein, & Spiga, 2011), ce qui n'est généralement pas possible avec les autres types de mesures de prise de risque. Administrée sous forme de jeu vidéo, la BART offre au participant une somme d'argent (réelle ou virtuelle) chaque fois qu'il gonfle un ballon dégonflé (p. ex., $0.25 par coup de pompe ou 0.3 cm). Cependant, le ballon peut exploser, auquel cas l'argent amassé pour l'essai en cours est perdu (le participant ne peut perdre d'argent, contrairement à l'IGT). Ainsi, plus le ballon est gonflé, plus grande sera la récompense à la fin de l'essai, mais chaque ballon a une probabilité d'explosion différente (variant de 1 à 128 coups de pompe, pour une moyenne de 64). C'est le participant qui décide quand il a suffisamment gonflé le ballon, auquel cas il empoche l'argent gagné pour l'essai (30 essais au total). Le nombre de coups de pompe représente la principale variable dépendante. Après quelques essais, le participant réalise habituellement qu'un certain nombre de coups de pompe est optimal pour faire plus de gains que de pertes. Par contre, certains participants tentent obstinément de trop gonfler le ballon, ce qui mène à des pertes à long terme. Des résultats faibles à cette tâche sont significativement associés à des comportements ou à des traits liés à la délinquance, tels qu'une forte prise de risque dans le monde réel (Lejuez, Aklin, Zvolensky, & Pedulla, 2003), la psychopathie (Hunt, Hopko, Bare, Lejuez, & Robinson, 2005) et des troubles de dépendance (Hopko et al., 2006). La BART est considérée comme la meilleure tâche de prise de risque développée à ce jour (Matusiewicz & Lejuez, 2012).

À noter que la majorité des tests décrits sont disponibles en format logiciel téléchargeable, vendus individuellement, sans les normes, par la compagnie Inquisit (http://www.millisecond.com).

Choisir la bonne mesure d'impulsivité

L'impulsivité est donc une entité clinique multidimensionnelle dont les facteurs ne peuvent être évalués de la même façon. Une première distinction à faire est celle entre les questionnaires d'impulsivité et les épreuves directes. Il a déjà été pensé que ces deux types de mesures offraient des résultats similaires, mais ce n'est pas le cas. Un grand nombre d'études ont maintenant démontré que les mesures d'impulsivité basées sur des questionnaires ne corrèlent pas avec celles obtenues à partir d'épreuves informatisées. Ce ne sont pas les mêmes aspects cliniques qui sont évalués (Cyders & Coskunpinar, 2012; Dolan & Fullam, 2004; Edman, Schalling, & Levander, 1983; Enticott et al., 2008; Gerbing et al., 1987; Helmers et al., 1995; Leshem & Glicksohn, 2007; Malle & Neubauer, 1991; Parker & Bagby, 1997; Reynolds, Ortengren, Richards, & de Wit, 2006; Stanford et al., 2009; White et al., 1994). L'évaluation de l'état impulsif, en particulier auprès d'une population hostile ou ayant un trouble mental, ne devrait pas s'effectuer à l'aide d'un questionnaire, mais bien à l'aide d'une mesure comportementale directe.

Quant aux mesures comportementales directes d'impulsivité, il semble qu'elles peuvent être divisées entre deux grands types, soit celles qui évaluent l'impulsivité motrice, l'impulsivité attentionnelle et la vigilance, d'une part, et celles qui évaluent des caractéristiques peut-être plus associées à la personnalité, telles que l'évitement des délais, la prise de risque et l'insouciance, d'autre part. Très peu d'études de validation ou d'analyses factorielles sont disponibles à ce sujet, mais les principales mesures informatisées d'impulsivité motrices ou attentionnelles ne semblent pas corréler avec celles de l'évitement des délais ou de la prise de risque (Dougherty et al., 2009; Lane, Cherek, Rhoades, Pietras, & Tcheremissine, 2003, Reynolds et al., 2006). Ceci démontre, une fois de plus, l'importance de choisir des mesures d'impulsivité en fonction de la facette étudiée.

La réalité virtuelle, approche neuropsychologique de l'avenir?

La réalité virtuelle offre également des avantages pour évaluer l'impulsivité. L'immersion d'une personne dans un environnement permet non seulement d'obtenir une validité écologique inégalée, mais aussi de mesurer plusieurs aspects de l'impulsivité à la fois, sans même que le participant en soit conscient. Par exemple, nous avons développé un appartement virtuel qui permet d'évaluer simultanément l'impulsivité motrice (paradigme de Go-no-go), la sensibilité à l'interférence interne (effet Stroop bimodal) et la sensibilité à l'interférence externe (présence de plusieurs éléments de l'environnement qui se manifestent de façon auditive ou visuelle, tel un téléphone qui vibre ou une horloge qui sonne l'heure), et ce, en moins de dix minutes (Henry, Joyal, & Nolin, 2012). Ce type de tâches réalistes colle plus aux activités de la vie quotidienne que les tests neuropsychologiques classiques, et elles permettent des mesures supplémentaires potentiellement importantes, telles que les mouvements de tête ou d'yeux (Henry, Jacob, Lacoursière-Girard, Nolin, & Joyal, 2013). En outre, elles sont plus agréables à effectuer. Elles peuvent être administrées en milieu carcéral ou médico-légal. Il est donc probable que la réalité virtuelle soit de plus en plus utilisée pour évaluer l'impulsivité comportementale.

CONCLUSION

Tel que vu, l'impulsivité est un trait ou un état multidimensionnel dont l'évaluation nécessite plusieurs instruments. L'important est de choisir les bons instruments en fonction des facettes à mesurer et de la clientèle à évaluer. Éventuellement, il sera possible de compléter l'évaluation par des mesures médicales, par exemple, le profil génétique, les taux de certains neurotransmetteurs, les patrons d'ondes cérébrales et l'imagerie fonctionnelle.

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Chapter 3

Development and initial assessment of a new paradigm for assessing cognitive and motor inhibition: The Bimodal Virtual-Reality Stroop

Development and initial assessment of a new paradigm for assessing cognitive and motor inhibition: The Bimodal Virtual-Reality Stroop

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ABSTRACT

Assessing and predicting inhibition in adults is a common assignment for clinicians. However, there is no single measure of inhibition that is complete, sensitive and enjoyable. The main goal of this study was to develop a virtual reality neuropsychological task (the VR-Stroop) capable of measuring both cognitive (control of internal and external interference) and motor inhibition (a go no-go paradigm with reaction time variation, commission errors and omissions). Preliminary data obtained with 71 healthy adult participants confirmed that the VR-Stroop is capable of eliciting the Stroop effect with bimodal stimuli. Initial validation data also suggested that measures of the VR-Stroop significantly correlate with measures of the Elevator counting with distractors, the Continuous Performance Task (CPT-II), and the Stop-it task. Finally, regression analyses indicated that commission errors and variability of reaction times at the VR-Stroop were significantly predicted by scores of the Elevator task and the CPT-II. These preliminary results suggest that the VR-Stroop is an interesting measure of cognitive and motor inhibition for adults, although confirmatory investigations are warranted.

Keywords: Virtual reality; inhibition; impulsivity; neuropsychology; apartment Stroop; go no-go, adults.

1. Introduction

Lack of inhibition (or impulsivity) is among the most common manifestations of mental disorder diagnoses (APA, 2000; Moeller et al., 2001). It is also one of the most common behaviors assessed by clinicians (e.g. Lezak et al., 2004). Yet, available measures of inhibition/impulsivity are often considered unsatisfactory or incomplete as they are associated with low sensitivity and poor predictive value, especially among clinical populations (e.g. with psychiatric and/or neurological impairments; Mathias et al., 2008; Moeller et al., 2001; Reynolds et al., 2006). The main goal of this study was to develop a single, yet more complete, assessment of inhibition/impulsivity using virtual reality.

A first factor explaining the difficulties of measuring inhibition/ impulsivity is the traditional use of questionnaires and verbal self-reports (e.g. the Barratt Impulsivity Scale; Patton et al., 1995; the I7 subscale, Eysenck et al., 1985; the UPPS impulsive behavioral scale, Whiteside et al., 2005). Results from these measures depend heavily on the collaboration and comprehension of the examinee, which is not always attainable in certain clinical settings (e.g. forensic and general psychiatry). Also, questionnaires tend to reflect long term traits of impulsivity (as opposed to acute states), and their results often fail to correlate with those of direct (behavioral) measures of acute impulsivity (e.g. Gerbing et al., 1987; Reynolds et al., 2006; Horn et al., 2003). Thus, computerized assessments are better suited to evaluate acute states of inhibition/impulsivity, especially among clinical populations (e.g. Mathias et al., 2008; Moeller et al., 2001).

A second factor explaining the difficulties of developing a satisfying measure of inhibition/impulsivity is the relative complexity of the constructs. Different clinical and research backgrounds, ranging from experimental psychology (e.g. Logan and Cowan, 1984; Patton et al., 1995), to adult psychiatry (e.g. Moeller et al., 2001), and developmental psychology (e.g. Nigg, 2000; Barkley, 1997) offered different theoretical accounts of inhibition and its corollary, impulsivity. Thus, several subtypes of both inhibition (e.g. behavioral vs. cognitive, intentional vs. non intentional, interference control vs. dyscontrol, Nigg, 2000; behavioral vs. interference control vs. cognitive, Kipp, 2005), and impulsivity have been proposed during the past half century (e.g. motor, attentional, and unplanning; Barratt, 1965; Patton et al., 1995; lack of inhibitory control, low decision time, sensation seeking and low persistence; Buss and Plomin, 1975; urgency, lack of premeditation, lack of perseverance and sensation seeking; Whiteside and Lynam, 2001). Overall, however, direct measures (i.e. behavioral) of inhibition and impulsivity are known to either assess cognitive inhibition or motor control (e.g. White et al., 1994). It would be best to develop a task capable of measuring both cognitive inhibition and motor control.

Cognitive inhibition is sometime viewed as the capacity to inhibit access of irrelevant material in working memory (a rather higher-order capacity directly associated with executive functioning; Kipp, 2005), or decision-making capacities (more closely associated with risk taking and/or thrill seeking; e.g. Bechara and van der Linden, 2005). Most commonly, cognitive inhibition is considered as the capacity to control interference from external (environmental) or internal (e.g. intrusive thoughts) stimuli (e.g. Kipp, 2005). In that sense, interference control is a process that helps maintaining attention focussed on a task in spite of distracters. Thus, the best would be to measure both type of interference with the same task. With virtual reality (VR), it is relatively simple to assess external interference with introduction of surrounding distracters within the environment. External distracters (auditory and/or visual elements) render the task environment more sensitive and more ecologically valid than traditional settings (Adams et al., 2009; Nolin et al., 2009). Moreover, distracters provoke head movements, allowing a better detection of subtle deficits among clinical populations (Nolin et al., 2009, 2012). Therefore, a main advantage of virtual neuropsychological tasks is to evaluate skills and abilities in an environment that appears more sensitive and similar to the real world (e.g. Matheis et al., 2007). As for control of internal interference, it is best measured with the Stroop task, the most widely used assessment of cognitive inhibition and interference control for adults (e.g. MacLeod and MacDonald, 2000; Strauss et al., 2006). That task is based on the classic Stroop effect (Stroop, 1935; MacLeod, 1991), related with the normal habit of automatically reading a written word. When the name of a color and the ink color of the name differ (e.g. the word BLUE is written in red) and a person must name only the ink color, either his/her response time or the number of errors (or both) increase compared to trials where the name and its ink matched. Because inhibition assessments are much more numerous for children than adults (e.g. Simpson and Riggs, 2005; Korkman et al., 1998; Manly et al., 1999; see Lezak et al., 2004 for a compendium), and the Stroop effect is stronger in adults than children (being based on reading automaticity; e.g. MacLeod, 1991), a virtual environment adapted for adults with measures based on the Stroop effect was chosen. Pairing environmental distracters with the Stroop measure, it becomes possible to assess interference control for both external and internal stimuli. Thus, a single instrument could measure both motor impulsivity and cognitive impulsivity. Another virtual reality Stroop task with distracters was recently developed by Parsons et al. (2011), although the Stroop stimuli are unimodal (visual only), and the environments are different (Iraqi/Afghani war zones for army veterans). Using unimodal stimulus presentation implies that at least three different response keys are needed (three different colors). In this study, a VR-Stroop assessment with bimodal stimuli was developed to integrate a measure of motor control, which implies a single response key (go/no-go reaction times). Moreover, a regular environment has to be used to improve environmental ecological validity for the general population.

Motor control is generally viewed as the capacity to physically and voluntarily withhold a prepotent or ongoing motor response (e.g. Evenden, 1999; Dougherty et al., 2009). Motor control is best evaluated with computerized measures, which are generally based on go no-go paradigms (e.g. CPT-II, Conners et al., 2003; the TOVA, Leark et al., 2007; The Stop-it task; Verbruggen et al., 2008). The most commonly used variable for motor control assessment is the commission error, a reactive act performed with low reaction time and reflection, associated with low impulse control, high risk taking tendencies, poor decision making, low gratification delay capacities and weak resistance to temptation (e.g. Kipp, 2005; White et al., 1994). Motor inhibition and commission errors are closely dependent upon integrity of brain circuits involving the lower parts of the frontal lobes (e.g. Bechara and van der Linden, 2005; Horn et al., 2003). Another interesting approach with go no-go paradigms is to consider intra-individual (and intra-test) variability of reaction times, which is associated with certain types of neurological conditions such as Attentional Deficit and Hyperactivity Disorder (ADHD and the so-called sluggish cognitive tempo; e.g. Carlson and Mann, 2002).

Go no-go paradigms might also be used to indirectly assess the capacity of inhibition processes with stop-signal tasks (Verbruggen et al., 2008). The Stop-it task in particular allows to determine the time required between a visual go signal and a auditory no-go signal for an individual to withhold a response, which corresponds to the Stop-Signal Reaction Time (SSRT), an index of inhibition capacities (Logan and Cowan, 1984; Logan et al., 1997; Verbruggen et al., 2008). The Stop-it is generally considered as the best measure of motor inhibition (e.g. Nolan et al., 2011). It is also worth noting that good performances at the Stop-it activate brain regions that are not identical (they only partially overlap) with those associated with good performances at the CPT-II (Swick et al., 2011). Thus, these tasks are not measuring exactly the same construct and might be used concurrently.

The main problem with go no-go paradigms is their notorious tediousness and monotony for the examinee. First, they were generally developed to assess vigilance (the capacity to maintain attention focussed for a relatively long period of time), rendering the assessment long (up to 20 min) and boring. Second, the ecological validity and interest for their environments (typically Xs and Os appearing on a black screen of a computer in a quiet experimental room) are particularly low. The use of virtual reality should vastly improve these aspects of the assessment.

Finally, there are important differences between the concepts and measurements of interference control (as measured with the Stroop), and motor impulsivity (as measured with go no-go paradigms; e.g. Perugini et al., 2000; van Mourik et al., 2005). Given that associations between the Stroop effect and other types of inhibition capacities might be weak (e.g. Heflin et al., 2011), it would be interesting to develop a task capable of measuring more than one subtype of inhibition/impulsivity.

The first objective of this study was to confirm that a Stroop effect might be elicited with a VR task based on bimodal stimuli. The main goal was to develop a single impulsivity measure assessing control of internal interference (Stroop effect), control of external interference (environmental distracters), and motor inhibition (simple reaction times based on a go-no go paradigm). A third goal of this study was to conduct a first-step convergent validation of the VR task with a small group of participants and traditional impulsivity measures.

2. Methods

This study was conducted in two phases: (1) a pilot part during which optimal experimental conditions were determined (e.g. comfort of the experimental room, difficulty levels of the task, clarity of instructions; best inter-trial intervals -ISI) and program bugs were fixed and (2) a preliminary validation phase during which additional participants were assessed with the VR-Stroop and traditional impulsivity/inhibition tasks.

2.1. Participants

A total of 71 volunteers participated in the study. The pilot phase was conducted with 33 adults recruited among summer students, research assistants, and their friends (mean age: 26.1 ± 9.2, 10 males, 23 females). The validation phase was conducted with 40 additional adult volunteers (minus two participants with invalid data), recruited among the general population through newspaper advertisements, relatives or acquaintances of research assistants, co-workers of relatives, undergraduate students and university non-academic staff (mean age: 33.8 ± 15.2, range 19–58 years old; 14 males, 24 females; 15 full-time workers, 15 full-time students, 8 others). The research was completed in accordance with the Helsinki Declaration.

2.2. Measures

All participants were assessed with the following impulsivity/inhibition measures: (1) the conventional Stroop task (D-KEFS version; Delis et al., 2001 – measure of control for internal interference), (2) the Elevator Counting task with distraction (TEA; Robertson et al., 1994 – measure of control for external interference); (3) the Continuous Performance Task second edition (CPT-II; Conners et al., 2003 – measure of reaction times, commissions, omissions and variability); (4) the Stop-it task (Verbruggen et al., 2008 – measure of inhibition) and (5) the VR-Stroop task (Henry et al., 2011). Assessment order was counterbalanced across participants. Assessments were given by university research assistants who received specific training and supervision to do so.

The Stroop task, D-KEFS version (Color Word Interference Task, Delis et al., 2001) is very similar to the original task (Stroop, 1935). It is considered as a measure of cognitive (or internal interference) control assessing the capacity of a person to suppress a habitual response in favor of a less familiar one while maintaining a goal in mind (Strauss et al., 2006). The task includes 4 conditions but only the data from the first and third conditions were analyzed for the present study in order to match both conditions of the virtual task. On the first condition, participants must name the color of color blocks (red, blue or green) presented in pseudo-random order as fast as they can. That condition assesses color-blindness selective attention and speed processing. The third condition requires to name the color of the ink in which color words (same colors as in condition 1) are printed (for example, RED printed in blue). That condition assesses cognitive interference, the “Stroop effect”.

The Elevator Counting with distracters is a subtest of the Test of Everyday Attention battery (TEA, Robertson et al., 1994; Pearson Assessments, 1998). It is a task of selective attention and working memory with external interference in which participants have to use an imaginary Elevator with an inoperative floor indicator (McAnespie, 2001). In order to know on which floor they are on, auditory stimuli are presented to the examinee: low-pitched tones must be counted as the Elevator going up one floor, while interspersed high-pitched tones (distracters) must be ignored. The task has 10 trials and one point is given for each correctly counted string.

The Continuous Performance Task-II (Conners et al., 2003; Multi-Health System, 2000). The CPT-II is a 14 min computer-administered task used to assess motor impulsivity and vigilance (Lezak et al., 2004). Participants must press a button as quickly as possible in response to a target stimulus (a letter appearing in the center of the screen) except when the letter X is presented. A total of 360 stimuli are presented, 36 of which are nontarget ("X") refraining the participant from responding. Each letter is presented for a total of 250 ms and interstimulus interval rates vary between 1, 2 or 4 s. Motor impulsivity is measured with commission errors and high reaction times while inattention is measured with omission errors and slow response style. Vigilance is related to the stability of responses across blocks of trials. Mean reaction times for good responses and total responses are also computed, as well as their variations across blocks of trials.

The Stop-it task (Logan et al., 1997; Verbruggen et al., 2008). This measure is considered as one of the best computerized measure of motor inhibition (e.g. Nolan et al., 2011). The stop-it is an indirect measure of inhibition processing integrity based on an algorithm that gradually adapts to the mean simple reaction time of each participant. The goal is to induce errors in approximately 50% of the trials, no matter what the mean reaction time of a particular participant is (Verbruggen et al., 2008). The primary task consists of simple reaction time and shape discrimination where a left key has to be pressed in response to the appearance of a square, and a right key when the shape is a circle. These are the no-signal trials. On 25% of trials, an auditory signal (a beep sound) succeeds more or less rapidly the visual stimulus, in which cases participants have to withhold their motor response (stop-signal trials). A lack of inhibition will manifest either as a too quick "go" response or a too slow "stop" response (Verbruggen et al., 2008). The program varies the time elapsed between the go stimuli and the stop stimuli as a function of the response speed of each participant. These stop signal delay variations greatly improve sensitivity of the task (Logan and Cowan, 1984; Logan et al., 1997) stop-signal delays increase by 50 ms when the participant correctly inhibits a response, rendering the next trial harder to inhibit or decrease by 50 ms after commission errors, rendering the subsequent trial easier, until 50% of correct responses is reached (Verbruggen et al., 2008; Logan et al., 1997). The Stop-Signal Reaction Time (SSRT) and the Stop-Signal Delay (SSD) were considered here.

The VR-Stroop (ClinicaVR: Apartment Stroop) task was developed in collaboration with Digital MediaWorks (www.dmw.ca) as an attempt to obtain a more complete inhibition task, and to improve sensitivity of impulsivity assessments (Henry et al., 2011). The environment is the interior of a virtual apartment (see Fig. 1). Participants are seated in the living room, in front of a flat-screen TV set, a kitchen and a window. A head-mounted display (HMD) was used (eMagin Z800 visor) to recreate a 3D-like effect and participants were allowed to look 360° around themselves and explore the environment by turning their head. The task is based on the Stroop effect (and measures internal cognitive interference), with go no-go components (reaction time, commission errors and omission errors, reaction time variability) and external interference (audio–visual environmental stimuli).

It consists of two conditions. In the first condition, a series of color rectangles appear on the television screen (blue, red or green, pseudo-randomly) while names of colors (blue, red or green) are verbally stated through the computer speakers (male or female voice, the female voice was chosen for all participants), at the same time with the same pace (bimodal presentations). Participants must click on the left button of a mouse with their preferred hand as quickly as possible when the color named (audio stimulus) matches the color shown (visual stimulus). They must withhold their response in mismatched trials. A total of 144 stimuli are presented, including 72 targets (go responses). During the task, distracters appear in different areas of the environment (center (C), left (L) or right (R)). Some distracters are audio–visual (School Bus passing on the street (R); SUV (R); iPhone on the table (C); Toy Robot on the floor (C)), others are auditory (Crumple Paper (L); Drop Pencil (L); Doorbell (L) Kat Clock (L) Vacuum Cleaner (R) Jack Hammer (R) Sneeze (L) Jet Noise (C)) and some are visual (Paper plane (L → R), Woman walking in the kitchen (C)). That condition was designed to assess reaction times (simple and complex), selective attention (matching the auditory and visual stimuli), and external interference control (environmental distracters). The duration of condition 1 is 4.8 min. Inter-Stimulus Intervals (ISI) of 2000 ms and 1000 ms were used in the pilot phase to determine the most efficient.

In the second condition, color words are presented on the screen, written with matched ink color (BLUE written in blue, congruent trial) or different ink color (e.g. BLUE written in red, incongruent trial – see Fig. 1). The colors are stated by the same voice as in condition 1 and participants must click on the mouse when the color heard is the same as the ink color (target stimuli, congruent or incongruent) but not the color word. A total of 144 stimuli are presented, including 72 targets (go responses), divided in 36 congruent and 36 incongruent stimuli. During the task, the same distracters as in condition 1 appear in the environment. That condition was designed to assess cognitive interference (Stroop effect) in addition to the measures of condition 1 (go no-go variables and external interference). The duration of condition 2 is also 4.8 min, for a total task duration of 9.6 min. Measures include: (1) the mean total reaction time; (2) the mean reaction time for correct responses; (3) variation (standard deviations) of reaction times; (4) variation (standard deviations) of reaction times for correct responses (5) the number of correct responses; (6) the number of commission errors and (7) the number of omission errors.

Fig. 1. Capture of the VR-Stroop environment (during condition 2). (For interpretation of the references to color in the text, the reader is referred to the web version of the article.

Questionnaires. After completion of the neuropsychological tasks, participants ($n = 71$) filled two questionnaires describing their VR experience: (1) the realistic subscale of the Presence Questionnaire (Witmer and Singer, 1994; adapted version of UQO Cyberpsychology Laboratory; Robillard et al., 2002) evaluated the realism of the VR task with 7 questions arranged on a Likert scales (from 1 to 7) and (2) the Simulator Sickness Questionnaire (Kennedy et al., 1993; adapted version of UQO Cyberpsychology Laboratory; Bouchard et al., 2007) assessed the occurrence, nature and severity of sickness symptoms induced by VR environments with 16 items to be rated on a scale from 0 to 3.

2.3. Statistical analyses

Given the preliminary and exploratory nature of this study (only one group of participants was involved and only 38 participants were included), statistical analyses will focus more on avoiding type II errors (masking genuine effects with restrictive analyses) than type I errors (reporting spurious or fortuitous statistical significance). The primary results (verification of a Stroop effect with the VR-Stroop) will be analyzed with a series of paired t-tests with the level set at 0.001 because the number of comparisons (10) will exceed the number of participants divided by 10 (approximately 4 comparisons are allowed with a minimum of 10 participants per comparison).

The second wave of results (preliminary validation the VRStroop) will be analyzed with correlations between fundamental variables of the different inhibition measures (see Parsons and Rizzo, 2008 for a similar approach for initial validation of a VR task). As an attempt to keep the number of correlations at the lowest possible number, the following variables were chosen on the basis of their theoretical importance: the mean time completion of the D-KEFS Color-Word Interference Task; the mean number of omissions and commissions, the mean reaction time and the rate (%) of non ADHD diagnoses of the CPT-II; the Stop-Signal Reaction Time (SSRT) and Stop-Signal delay (SSD) of the Stop-it; and the total score of the TEA Elevator counting with distractions task. From the VR-Stroop, the mean number of correct responses, commissions, omissions, double clicks, and the mean reaction time total and for correct responses, and variation of reaction time (total and for correct responses) were considered.

The third and final stage of analyses will assess the capacity of traditional measures to predict the level of virtual measures with multiple regressions. Because complete data for only 38 participants were available, only 4 variables (approximately 10 participants per variable) will be selected from those significantly correlating as predictors of VR-Stroop performances. The predictive values of these 4 variables will be assessed for condition 1 and condition 2 of the VR-Stroop and only the most significant model for each condition will be retained.

2.4. Ethical considerations

The present study was approved by the ethical committee of the university and each volunteers signed a consent form after explanation of the purposes and procedures were given. Participants in the validation study (part two) received $15 in compensation.

3. Results

3.1. Pilot results

Pilot results showed that an ISI of 2000 ms was associated with a ceiling effect. The task was too easy for control participants, with high ratios of correct/incorrect responses, low standard deviations, and no differences between conditions (mean numbers of correct responses in condition 1: 71.6 ± 0.7 vs. 69.9 ± 6.6 in condition 2; $p > 0.1$; commission errors during condition 1: 2.21 ± 3.2 vs. 2.24 ± 2.7 during condition 2; $p > 0.1$). Thus, the ISI was set at 1000 ms.

3.2. Primary results

With an ISI of 1000 ms, error rates were higher (15% or more), and differences between conditions were statistically significant for the mean numbers of correct responses (67.1 ± 4.9 vs. 62.3 ± 7.8; $t\,(1, 37) = 4.79$, $p < 0.0001$, respectively), the mean reaction times for correct responses (0.5833 ± 0.0488 s vs. 0.6407 ± 0.0659 s; $t\,(1, 37) = -6.38$, $p < 0.0001$, respectively), the mean variations of reaction time for correct responses (0.127 ± 0.04 s vs. 0.156 ± 0.04 s, $t\,(1, 37) = -4.28$, $p < 0.0001$, respectively), the mean numbers of omissions (3.5 ± 3.9 vs. 8.3 ± 6.8, $t\,(1, 37) = -5.30$, $p < 0.0001$, respectively), and the mean variations for total reaction time (0.127 ± 0.06 s vs. 0.191 ± 0.08 s, $t\,(1, 37) = -4.14$, $p < 0.0001$, respectively). The mean numbers of commissions also differed between condition 1 (6.9 ± 4.5) and condition 2 (7.5 ± 5.3), although standard deviations were high and the magnitude of difference was low and not significant ($t\,(1, 37) = -1.09$, $p < 0.2$). During condition 2, the mean reaction times (0.599 ± 0.054 s vs. 0.691 ± 0.099 s, $t\,(1, 37) = -7.22$, $p < 0.0001$) and the mean variations of reaction (0.126 ± 0.037 s vs. 0.164 ± 0.049 s, $t\,(1, 37) = -5.06$, $p < 0.0001$) significantly differed between congruent and incongruent trials (respectively), suggesting an internal interference effect.

3.2.1. Validation correlations

Significant correlations between variables of the tasks appear in Table 1 (condition 1) and Table 2 (condition 2). As illustrated in the Tables, scores in condition 1 (color blocks) of the VR-Stroop were mainly associated with variables of the Elevator counting with distractions and the mean reaction time of the CPT-II (Table 1), while scores in condition 2 (color words) were associated with variables of the Elevator counting with distractions, the conventional Stroop task and the Stop-it task (Table 2). Certain variables of condition 2 were also associated (negatively) with variables of the CPT-II, including the rate of non-ADHD diagnoses (Table 2).

Table 1

Correlations between traditional measures of impulsivity and the condition 1 of the virtual reality Stroop (bold = $p < 0.05$ uncorrected).

VR Stroop	Stroop[a]	CPT-O[b]	CPT-C[c]	CPT RT[d]	%ADHD[e]	SSD[f]	SSRT[g]	Elevator[h]
Correct Responses (CR)	*r* = -0.085	*r* = 0.036	*r* = 0.158	***r* = 0.381**	*r* = -0.099	*r* = 0.172	*r* = -0.202	***r* = 0.385**
	p = 0.611	*p* = 0.828	*p* = 0.343	***p* = 0.018**	*p* = 0.555	*p* = 0.301	*p* = 0.224	***p* = 0.017**
RT on CR	*r* = 0.202	*r* = 0.186	*r* = -0.175	***r* = 0.420**	*r* = -0.319	*r* = 0.169	***r* = 0.337**	*r* = -0.195
	p = 0.223	*p* = 0.263	*p* = 0.293	***p* = 0.009**	*p* = 0.051	*p* = 0.311	***p* = 0.039**	*p* = 0.241
RT var on CR	*r* = 0.131	*r* = 0.007	*r* = -0.137	***r* = 0.379**	*r* = -0.053	*r* = -0.295	*r* = 0.320	***r* = -0.394**
	p = 0.434	*p* = 0.969	*p* = 0.411	***p* = 0.019**	*p* = 0.750	*p* = 0.072	*p* = 0.050	***p* = 0.014**
Commissions	***r* = 0.459**	*r* = 0.076	*r* = -0.010	*r* = 0.072	*r* = 0.098	*r* = -0.069	*r* = 0.023	***r* = -0.546**
	***p* = 0.004**	*p* = 0.648	*p* = 0.953	*p* = 0.669	*p* = 0.560	*p* = 0.680	*p* = 0.889	***p* = 0.0001**
Omissions	*r* = 0.086	*r* = 0.003	*r* = -0.078	*r* = 0.305	*r* = 0.084	*r* = -0.178	*r* = 0.202	***r* = -0.361**
	p = 0.609	*p* = 0.986	*p* = 0.643	*p* = 0.063	*p* = 0.617	*p* = 0.286	*p* = 0.224	***p* = 0.026**
Double Clicks	*r* = 0.184	*r* = 0.105	*r* = -0.103	***r* = 0.374**	*r* = -0.043	*r* = -0.087	*r* = 0.279	***r* = -0.352**
	p = 0.270	*p* = 0.530	*p* = 0.540	***p* = 0.021**	*p* = 0.800	*p* = 0.603	*p* = 0.089	***p* = 0.030**
RT var Total	*r* = 0.127	*r* = 0.027	*r* = -0.255	***r* = 0.327**	*r* = 0.051	*r* = -0.213	*r* = 0.197	*r* = -0.308
	p = 0.448	*p* = 0.872	*p* = 0.123	***p* = 0.045**	*p* = 0.762	*p* = 0.199	*p* = 0.236	*p* = 0.060
RT Total	*r* = 0.105	*r* = 0.151	*r* = -0.213	*r* = 0.128	*r* = 0.049	*r* = 0.267	*r* = -0.051	*r* = 0.261
	p = 0.531	*p* = 0.367	*p* = 0.200	*p* = 0.444	*p* = 0.772	*p* = 0.105	*p* = 0.760	*p* = 0.113

[a] D-KEFS Color-Word Interference Task; mean time completion
[b] CPT-II; number of omissions
[c] CPT-II; number of commissions
[d] CPT-II; mean reaction time
[e] CPT-II; rate of non ADHD diagnoses
[f] Stop-it; Stop-Signal delay
[g] Stop-it; Stop-Signal reaction time
[h] TEA Elevator task; mean number of correct responses

Table 2

Correlations between traditional measures of impulsivity and the condition 2 of the virtual reality Stroop (bold = $p < 0.05$ uncorrected).

VR Stroop	Stroop[a]	CPT-O[b]	CPT-C[c]	CPT RT[d]	%ADHD[e]	SSD[f]	SSRT[g]	Elevator[h]
Correct Responses (CR)	**r = -0.455**	r = -0.101	r = 0.037	r = -0.222	r = 0.103	r = 0.053	r = -0.228	**r = 0.454**
	p = 0.004	p = 0.545	p = 0.828	p = 0.180	p = 0.539	p = 0.751	p = 0.169	**p = 0.004**
RT on CR	**r = 0.377**	r = -0.050	r = -0.066	r = 0.455	**r = -0.453**	r = -0.014	**r = 0.497**	r = -0.228
	p = 0.020	p = 0.765	p = 0.692	p = 0.004	**p = 0.004**	p = 0.932	**p = 0.001**	p = 0.168
RT var on CR	**r = 0.498**	r = 0.013	r = 0.109	r = 0.246	**r = -0.345**	r = -0.283	**r = 0.455**	**r = -0.617**
	p = 0.001	p = 0.937	p = 0.513	p = 0.136	**p = 0.034**	p = 0.085	**p = 0.004**	**p = 0.0001**
Commissions	**r = 0.475**	r = 0.006	r = 0.046	r = 0.165	r = 0.082	r = -0.168	r = 0.180	**r = -0.575**
	p = 0.003	p = 0.973	p = 0.786	p = 0.324	p = 0.626	p = 0.313	p = 0.279	**p = 0.0001**
Omissions	**r = 0.474**	r = 0.112	r = 0.005	r = 0.184	r = -0.087	r = -0.097	r = 0.263	**r = -0.488**
	p = 0.003	p = 0.503	p = 0.975	p = 0.269	p = 0.602	p = 0.562	p = 0.111	**p = 0.002**
Double Clicks	r = 0.180	r = -0.053	r = -0.206	r = 0.107	r = -0.183	r = 0.242	r = -0.120	r = -0.238
	p = 0.279	p = 0.750	p = 0.215	p = 0.521	p = 0.271	p = 0.143	p = 0.475	p = 0.150
RT var Total	**r = 0.542**	r = 0.000	r = 0.136	r = 0.226	r = -0.320	r = -0.070	**r = 0.438**	**r = -0.383**
	p = 0.0001	p = 0.998	p = 0.417	p = 0.172	p = 0.050	p = 0.676	**p = 0.006**	**p = 0.018**
RT Total	r = 0.256	r = 0.046	r = 0.221	r = 0.242	r = -0.286	r = -0.274	r = 0.311	r = -0.192
	p = 0.120	p = 0.782	p = 0.183	p = 0.144	p = 0.082	p = 0.097	p = 0.057	p = 0.249

[a] D-KEFS Color-Word Interference Task; mean time completion
[b] CPT-II; number of omissions
[c] CPT-II; number of commissions
[d] CPT-II; mean reaction time
[e] CPT-II; rate of non ADHD diagnoses
[f] Stop-it; Stop-Signal delay
[g] Stop-it; Stop-Signal reaction time
[h] TEA Elevator task; mean number of correct responses

3.2.2. Regression models

Based on the correlation matrices, the following 4 variables were retained as possible predictors of VR results: (1) the Elevator counting with distractions mean score; (2) the CPT-II mean reaction time; (3) the SSRT from the Stop-it and (4) the mean time completion of the D-KEFS Color-Word Interference Task. In condition 1 (color blocks), these 4 variables explained a significant portion of the variance of the reaction times for correct responses in the VR-Stroop ($R^2 = 27.6\%$; $p = 0.03$), although the solution was better for the commission errors ($R^2 = 37.9\%$; $p = 0.003$). The Elevator task score was significantly involved as a single variable (negatively; $\beta = -0.443$; $p = 0.011$), while a trend for a positive association was observed with the D-KEFS Stroop time completion ($\beta = 0.302$; $p = 0.07$). In condition 2, the same 4 variables explained a highly significant proportion (approximately half) of the variance for the RT variation on correct responses ($R^2 = 51.4\%$; $p = 0.0001$). The Elevator task mean score was also a significant inverse contributor ($\beta = -0.414$; $p = 0.007$), with the SSRT approaching significance ($\beta = 0.253$; $p = 0.06$).

3.2.3. Cybersickness symptoms and sense of realism

Overall, participants reported very few post-VR symptoms related with the task (mean: 6.8 ± 6.5, range 0–31, below 60th percentile according to the norms; Kennedy et al., 1993) with eye strain being the most frequent complaint (63% of the sample). The sense of presence was good (mean: 32.9 ± 7.7 range 12–49), slightly above the norm mean (29.45 ± 12.0).

4. Discussion

The main goal of this study was to develop a single VR measure of inhibition capable of assessing three different abilities: selective attention, control of cognitive interference, and motor inhibition. Although this preliminary study represents only the initial validation phase of the measure, interesting results emerged. First, results confirmed that the Stroop effect might be efficiently elicited in a VR environment. This conclusion is similar to that of Parsons et al. (2011), who used the Stroop effect in a war environment to show the usefulness of VR to assess cognitive and external interference. The present study further suggests that bimodal presentation of the stimuli also elicits the Stroop effect. That type of stimulus presentation (visual and auditory) lets the participant to continuously use the same unique response key, which in turn allows the examiner to assess motor impulsivity (simple reaction times, omissions, and commissions). Thus, the bimodal VR-Stroop seems capable of measuring internal interference control and motor inhibition simultaneously.

Initial validation of the task also suggests that bimodal VRStroop scores are associated significantly with important measures of impulsivity. More specifically, such fundamental variables as the Elevator counting mean score, the CPT-II mean reaction time, the SSRT, and D-KEFS interference mean time were all significant predictors of VR-Stroop scores. These results suggest that the VR-Stroop would be sensitive to one or more of these types of impulsivity.

Control of external interference and selective attention might also be assessed via head movements with the Head Mounted Display during the task. Although these variables were not analyzed for the present study, head movements provoked by environmental distracters in a virtual classroom were found to be the best detector of attentional deficits among children with mild brain injuries (Nolin et al., 2009, 2012).

Thus, the VR-Stroop might be useful for clinical purposes. On one hand, the task has the potential to detect a wider array of inhibition deficits than traditional neuropsychological measures and, on the other hand, it has the potential to discriminate between subgroups of clinical populations. These possibilities should be tested with different clinical and nonclinical groups of participants. For instance, the significant and negative association between the number of correct responses at the VR-Stroop and the rate of CPT ADHD diagnoses is intriguing. Variability in reaction times at the VR-Stroop was also associated with the CPT diagnosis of ADHD. Reaction time variability is linked with specific subtypes of ADHD (Carlson and Mann, 2002), and the capacity of the VR-Stroop to discriminate between controls and subtypes of ADHD persons should be tested in future investigations.

Overall, the bimodal VR-Stroop seems to represent a single, short (10 min), enjoyable, portable (with a laptop computer), and multi-component assessment of inhibition. Further investigations with measures of other type of cognitive functions (reasoning, deducing, planning, etc.) will help demonstrating the discriminant validity of the task. Concomitant assessments with psychophysiological measures (electrodermal conductance, eye-tracking, etc.) will also help confirming the validity of the construct. Currently, preliminary data suggest that the bimodal VR-Stroop could assess different aspects of inhibition, including selective attention, control of internal interference, and motor inhibition, either separately or as a global index of inhibition.

Conflict of interest statement

None.

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Chapter 4

Assessment of executive function in adolescence: A comparison of traditional tools and virtual reality.

Assessment of executive function in adolescence: A comparison of traditional tools and virtual reality.

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ABSTRACT

Paper-pencil tests are traditionally used in the assessment of EF; however, concerns have been raised as to whether these represent actual functioning in everyday life. Virtual reality (VR) environments offer a novel alternative for the assessment of cognitive function and therefore have the potential to enhance the evaluation of EFs by presenting individuals with stimuli that come closer to reproducing everyday situations. The aim of this study was (1) to establish which traditional (paper-pencil) EF tasks from the Delis-Kaplan Executive Function System are associated with performances on a VR-Stroop task and (2) to compare the paper-pencil EF tasks and the VR task in their ability to predict everyday EF. Thirty-eight typically developing adolescents aged between 13 and 17 years and their parents completed a VR task, paper-pencil tests and questionnaires. The results indicate that performance on the VR Stroop task is most closely associated with performance on traditional measures of inhibition and that performance on the VR task correlates with both traditional forms (paper-pencil and parent questionnaire) of EF assessment, but VR performance more accurately reflects everyday behavioural EF. VR appears to offer some advantages over traditional cognitive assessment and could be seen as a complementary ecological technique to traditional tests in the assessment of complex cognitive abilities.

Keywords: virtual reality, executive function, inhibition, assessment, adolescence, ClinicaVR: Classroom – Stroop.

1. Introduction

Adolescence is an important transitional stage characterized by intense physical, biological, cognitive and social changes. One of the most significant developmental aspects of adolescence is a substantial improvement in higher order mental processes, such as executive functions (EF). EF can be defined as the processes responsible for guiding, directing and managing cognition, emotion, and behavior, enabling the achievement of everyday goals, and include abilities such as planning, inhibition, initiation, organization, mental flexibility and shifting (Anderson, 2002; Fuster,2008; Gioia et al., 2000). The acquisition of such complex abilities allows adolescents to control their actions and thoughts and make them coherent with their internal goals (Crone, 2009). When the development of EF is delayed or disrupted, adolescents may experience cognitive impairments placing them at risk for maladaptive behavior and poor social skills (Anderson, 2002; Godfrey and Shum, 2000; Morgan and Lilienfeld, 2000).

Given the importance of EF for everyday interactions and goal achievement, the assessment of its various components constitutes one of the cornerstones of neuropsychological assessment. Standardized paper-pencil EF tests and questionnaires are traditionally used for this purpose and a number of comprehensive, developmentally appropriate tools exist that enable precise and direct evaluation of a variety of executive subskills in adolescence (e.g., Delis Kaplan Executive Functions System, Delis et al., 2001). However, concerns have been raised about whether traditional paper–pencil EF tests, often administered in controlled office settings, represent actual functioning in everyday life (Burgess et al., 2006; Nolin et al., 2009; Wilson, 1993). With few distractions, a quiet environment and one-on-one instructions, typical testing environments eliminate factors that usually affect cognitive functioning and inevitably reduce similarities to everyday environmental demands, thus affecting the predictive value of these tests (Chaytor and Schmitter-Edgecombe, 2003; Nolin et al., 2009). Recognizing that individuals' capabilities may fluctuate with environmental demands, questionnaires are often used in conjunction with direct assessment to identify problems in everyday functioning. The Behavioral Rating Inventory of Executive Function (BRIEF) questionnaire was developed to tap into cognitive and behavioral components of executive functioning in everyday situations and a variety of contexts (e.g., home, school, Gioia et al., 2000). Though not specifically designed to evaluate EF, other questionnaires provide indirect information concerning problematic behavioral aspects of EF. For example, the externalizing subscales of the Child Behavior Checklist (Achenbach and Rescorla, 2001) inform on rule-breaking behavior and ADHD-related symptoms, which may be linked to poor EF. While such questionnaires provide valid, standardized information on parental, teacher and self-perspectives, they are limited by subjective and third party biases. Concerns regarding the limitations of paper-pencil and questionnaire-based tests have encouraged the development of new forms of assessment that may come closer to reproducing real-life contexts and demands than traditional cognitive tests.

Virtual reality (VR) is a rapidly evolving technology that allows the immersion of participants into near-realistic situations whilst retaining control over the rigorous demands of direct assessment. A visor, projecting a dynamic, real-time, three-dimensional and entirely controlled environment, allows subjects to feel immersed and to navigate and interact during the administration of diverse tasks or scenarios. The strength of VR lies in its ability to make participants feel like they are 'present' in the environment projected to them via a head-mounted display. As such, VR is a potentially powerful tool for the assessment of cognitive functioning, and studies using VR technology are beginning to show evidence of the utility of virtually enriched environments as a novel and effective way to ecologically test cognitive function in children, adolescents, adults and various clinical populations (e.g., Henry et al., 2012; Matheis et al., 2007; Parsons et al., 2007; Pugnetti et al., 2009; Rizzo et al., 2000a; Schultheis et al., 2002). However, it is unclear how emerging cognitive VR paradigms compare to more traditional and standardized assessment tools.

Recent evolution in VR environments has allowed the development of specific paradigms for the measurement of cognitive skills such as attention and executive functions. Of these, the "Virtual Classroom" was originally developed as a controlled environment with varying levels of distraction in which attentional processes can be assessed in children (Rizzo et al., 2000b). During the task, the examinee sits at a virtual desk in a virtual school classroom containing desks, a chalkboard, a teacher, other students, and a large window. The environment also incorporates systematic and controlled presentations of typical classroom distracters, such as classroom noises and movement of virtual classmates or cars in the street. Attentional and executive tasks can be assessed by projection of stimuli onto the virtual classroom blackboard and via the teacher's voice, and performance is measured in terms of reaction times and number of errors (Rizzo et al., 2000b). For example, a Continuous Performance Task (CPT) can be presented to children and adolescents using the Virtual Classroom, and has been used to demonstrate the efficiency of VR assessment in distinguishing children with and without Attention Deficit/Hyperactivity Disorder (ADHD) (Moreau, 2006; Parsons et al., 2007; Pollak et al., 2009). Results on the VR-version of the CPT were shown to be similar to those obtained on more traditional assessment measures (Moreau,2006; Parsons et al., 2007; Pollak et al., 2009). In another study, the VR-CPT was more sensitive to inhibition deficits than its traditional form (Nolin et al., 2009). Performance on the VR-CPT has also been linked to ratings on parent-based questionnaires (Moreau, 2006; Parsons et al., 2007). Scores on the SWAN behavior checklist (Swanson et al., 2005), which assesses the presence of ADHD characteristics, and the Strength Difficulties Questionnaire (ADHD scale and Total problem scale, Goodman, 1999), were shown to correlate with the rate of errors on the VR-CPT.

Executive functions can also be assessed using a VR adaptation of the traditional Stroop task (Stroop, 1935) in the Virtual Classroom, which produces interference effects similar to the classic task (Rizzo et al., 2006). The Stroop effect is among the most well recognized interference control and inhibition phenomena and taps into important aspects of EF. The VR version has been shown to be more sensitive to attention and inhibition abilities than the traditional test, with individuals exhibiting longer reaction times and fewer correct responses (Parsons et al., 2001). However, studies comparing

EF performance on traditional standardized and VR tests remain scant. It is therefore unclear how such tests measure up to their well-established paper-pencil counterparts.

The aims of this study were therefore to (1) establish the relationship between performance on paper–pencil EF tests and the VR-Stroop task in healthy adolescents and (2) compare the paper–pencil Stroop test and the VR-Stroop task in their ability to predict everyday EF, as measured by a standardized EF questionnaire. It was expected that traditional paper–pencil inhibition tests would be significantly associated with VR performance, but that the VR-Stroop task would be more representative of everyday life executive functioning than the paper–pencil Stroop test.

2. Methods

2.1 Participants

Thirty-eight English-speaking, typically developing adolescents aged between 13 and 17 years (M = 14.69 years, SD = 1.23, 18 males) were recruited on a voluntary basis from regular school classrooms in Quebec, Canada. The participants were primarily Caucasian (85.3%), in a regular school curriculum, had IQ levels in the average range (M = 104.43, SD = 13.02, minimum = 85, maximum = 130) and were primarily from middle-class families. The participants presented no documented history of a diagnosed developmental, neurological or psychiatric condition that could influence cognitive functioning. All participants and their parents gave written informed consent before participation in this study, which was approved by the University of Montreal Research Ethics Committee.

2.2 Measures

The following measures were used to obtain a detailed description of the sample and to measure participants' global cognitive functioning and behavior.

2.2.1. ABCs Demographic Questionnaire

A standard developmental and demographic questionnaire, completed by the primary caregiver, was used to collect information on participants' medical, developmental, social and psychiatric history, parents' education, ethnicity, occupation, income and family constellation. Participants' socioeconomic status was calculated using their parents' scores on the Blishen socioeconomic index, which provides a score based on the average income and average education level associated with occupations in Canada. The index mean is 42.74 (SD = 13.3) and scores range from 17.81 (low SES) to101.74 (high SES; Blishen et al., 1987).

2.2.2. Child Behavior Checklist (CBCL, Achenbach and Rescorla, 2001)

This parent questionnaire assesses internalizing and externalizing problems on eight main scales (aggressive behavior, rule-breaking behavior (RBB), attention problems, thought problems, social problems, somatic complaints (SC), depressed, anxious/depressed) and six DSM-oriented scales (affective problems, anxiety problems, somatic problems, ADHD problems, oppositional defiant problems, conduct problems) and provides three summary scores (total problems, internalizing problems, externalizing problems, *T*-score, $M = 50$, SD = 10). Higher *T*-scores on a subscale indicate more behavioral problems. The RBB, SC and ADHD scales are reported here. The RBB and ADHD scales were used as indirect indicators of EF, while the SC scale was included to test the specificity of relationships between variables by including symptoms not related to EF.

2.2.3. Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 1999)

The two-subtest version of the WASI (matrix reasoning and vocabulary subtests) was administered to provide an estimate of Full Scale intellectual quotient (IQ; $M = 100$, SD = 15).

2.2.4. Simulator Sickness Questionnaire (SSQ, Kennedy et al., 1993)

This self-rated questionnaire was used to assess VR side effects, including motion sickness symptoms corresponding to three subscales (oculomotor, nausea and disorientation).

The following measures were used to assess executive functioning. The administration of the paper–pencil EF tests and VR-Stroop task were counter-balanced across participants to control for fatigue and practice effects.

2.2.5. Behavior Rating Inventory of Executive Function (BRIEF, Gioia et al., 2000)

This parent report questionnaire evaluates emotional and behavioral manifestations of executive dysfunction according to eight scales (inhibition, shifting, emotional control, initiation, working memory, planning, organization of materials and monitoring) and provides two index scores (Behavioral Regulation (BRI)and Metacognition (MI)) and one Global executive composite score(GEC) (T-scores, $M = 50$, SD = 10). A higher T-score on the BRIEF indicates more behavioral problems. In this study, the GEC, BRI, MI and the inhibition scale were used as indicators of everyday EF.

2.2.6. Delis–Kaplan Executive Function System (D-KEFS, Delis et al., 2001)

This standardized, paper–pencil assessment battery was used to assess various subcomponents of EF including:

Tower Test (TT, planning): The examinee's task is to move five disks varying in size across three vertical pegs to build a target tower in the fewest number of moves possible. In constructing the designated towers, the examinee has to follow two rules: (a) move only one disk at a time and (b) never put a larger disk on a smaller one. The number of rule violations and the first move time are reported ($M = 10$, SD = 3).

Color-Word Interference Test (CWIT, inhibition): This is a variant of the traditional Stroop procedure in which the participant is asked to name colored boxes (condition 1), read color-words printed in black ink (condition 2) and name the color of the ink in which color-words are printed (condition 3, inhibition). The number of errors (conditions 1 and 3) and completion time (condition 3) are reported here ($M = 10$, SD = 3).

Trail Making Test (TMT, cognitive flexibility): The examinee is asked to scan letters and numbers and cross out the number "3"(condition 1), connect numbers in numerical order (condition 2), connect letters in alphabetical order (condition 3), switch between connecting numbers and letters in alphabetical and numerical order (condition 4) and, connect circles linked by a dotted line as quickly as possible (condition 5). Condition 4 represents a measure of cognitive flexibility and the number of errors and completion time for this condition are reported ($M = 10$, SD = 3).

Verbal fluency (VF, fluency): The examinee has to generate words that begin with a specific letter (condition 1), state words that belong in a designated semantic category (condition 2) and generate words, switching between two different semantic categories (condition 3). The number of correct responses in condition 1 is reported ($M = 10$, SD = 3).

Twenty Questions (TQ, abstract reasoning): The examinee is presented with a stimulus page containing 30 common objects and has to identify the unknown target object using the fewest number of yes/no questions. The abstraction score reported for this task represents participants' ability to eliminate the most objects with the first question on each of the four trials ($M = 10$, SD = 3).

2.2.7. ClinicaVR: Classroom-Stroop

The virtual classroom was first developed by Rizzo et al. (2000b). It was revised by the Digital MediaWorks team (http://www.dmw.ca/) under the name ClinicaVR: Classroom-Stroop (see Henry et al., 2012, for a task description and initial validation results). This VR paradigm was used to assess EF using a Stroop-like task. Before each task, an avatar teacher in front of the virtual class states the instructions. The participants are asked to repeat the instructions and to try a short practice trial. In both conditions, interstimulus intervals of 1000 ms were used. Reaction time, omission errors, commission errors and correct answers are recorded.

Condition 1 (colored boxes): Boxes of three different colors are successively presented on the virtual chalkboard. The teacher states a color as each stimulus appears.

The participant has to click on the mouse if the color stated by the teacher corresponds to the color of the box presented on the chalkboard.

Condition 2 (colored words): In the second task, color words written in different colors of chalk are successively presented to the participant. As in condition 3 of the D-KEFS Color-Word Interference test, the stimuli are either congruent (e.g., the word BLUE presented in blue chalk) or incongruent (e.g., the word BLUE presented in red chalk). The participant has to click on the mouse only when the color stated by the teacher corresponds to the color of the chalk. For each condition, the number of commission errors was used to represent inhibition capabilities.

2.3. Virtual reality setup

A visor with a visual screen was placed on participants' heads and projected a three-dimensional environment. The visor allows full head movement and a complete 360°view of the virtual classroom. A tracking device, attached to the visor, transfers locational information to a computer, which updates the images presented to the user and increases the illusion that the subject is immersed in a real environment. A standard desktop computer was used to process the ClinicaVR Classroom program.

2.4. Statistical analyses

Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. Pearson partial correlations were conducted to examine the relationship between results on the VR-Stroop task, BRIEF, CBCL and D-KEFS subtests, while controlling for age. Multiple regressions were conducted to measure the degree to which the VR-Stroop task and the D-KEFS predicted scores on questionnaires of everyday EF (BRIEF) and behavior (CBCL). Specifically, commission errors on the CWIT and the box condition of the VR-Stroop task were used to predict scores on the BRIEF (inhibit scale, BRI, MCI, and GEC) and the CBCL (ADHD, RBB scales). Multiple regressions were also conducted to measure the degree to which performance on D-KEFS subtests had an effect on the main dependent variable, commission errors on the VR-Stroop task. The number of rule violations on the TT and the number of errors on the TMT and CWIT were entered into the model because they represent forms of commission errors, and therefore, disinhibition. Results corresponding to $p < .05$ were considered statistically significant.

3. Results

Descriptive results for all outcome measures are presented in Tables 3 and 4. No participant reported significant post-exposure VR sickness as determined by the SSQ. One outlier was found with a *Z*-score corresponding to 4.39 standard deviations above the mean score on the VR-Stroop task (box condition, commission errors) and was therefore excluded from the analyses.

Table 3

Results on EF outcome measures.

Variables	Minimum	Maximum	Mean	Std. deviation
BRIEF (T-scores)				
Global Executive Composite	35	85	48.41	12.09
Metacognition	35	86	49.68	12.86
Behavioral Regulation	37	78	46.97	10.66
Inhibit	41	81	48.06	10.13
CBCL (*T*-Scores)				
ADHD	50	68	53.54	6.81
Rule-Breaking Behavior	50	67	53.89	4.96
Somatic Complaints	50	68	54.89	5.89
D-KEFS (scaled scores)				
TT – 1st Move Time	8	13	10.26	1.29
TQ – Abstraction Score	5	18	9.55	3.38
VF Condition 1 – Correct responses	1	19	9.16	3.66
TMT Condition 4 – Completion Time	4	14	9.58	2.51
TMT-Condition 4 – Total error	4	12	10.11	2.36
CWIT Condition 3 – Completion Time	5	16	10.80	2.50
CWIT Condition 3 – Total errors	1	13	9.95	2.71
D-KEFS (cumulative percentages of normative sample with equal or higher scores)				
TT - Total Rule Violation	9	100	67.92	34.77
CWIT Condition 1 – Total errors	5	100	81.08	36.69

Table 4

Results on the VR Stroop measure (raw scores).

Variable	Minimum	Maximum	Mean	Std. deviation
Box condition				
Commission errors	0	47	9.6	8.52
Word condition				
Commission errors	1	33	14.73	8.82

3.1. Correlations between VR-Stroop task, D-KEFS subtests, BRIEF and CBCL

Commission errors were used to represent inhibition capabilities on the VR-Stroop task. The number of commission errors in both the box and word conditions of the VR-Stroop task was significantly associated with inhibition, as measured by the D-KEFS CWIT raw scores on condition 3 (completion time, commission errors)(see Table 5). Specifically, a greater number of commission errors on the VR-Stroop task was associated with longer completion time and a higher number of commission errors on the D-KEFS CWIT (condition 3). The number of commission errors in the box condition of the VR-Stroop task was also related to the number of rule violations on the D-KEFS TT; that is, a higher number of commission errors was associated with more rule violations.

Partial correlation (Table 5) using raw scores was used to explore the relationship between the number of commission errors in the VR-Stroop task and scores on the BRIEF. There were strong, positive, partial correlations between the number of commission errors in the box condition of the VR-Stroop task and the GEC, BRI, MI and Inhibit scales. As the number of commission errors increased in the VR-Stroop, adolescents were more impaired in their metacognition, behavioral regulation, inhibition/impulsivity control and their overall executive functioning, as measured by the BRIEF.

Partial correlation (Table 5) using raw scores was also used to explore the relationship between the number of commission errors in the VR-Stroop task and three subscales from the Child Behavior Checklist (CBCL). There were strong, positive, partial correlations between the number of commission errors in the box condition of the VR-Stroop task and scores on the RBB and ADHD scales; greater attention deficits and rule-breaking behavior were significantly associated with increased commission errors in the VR-Stroop task. No correlation was found between the VR-Stroop task and the SC subscale. This correlation was conducted to verify that the VR-Stroop task correlates specifically with EF indicators and not generally with other behavioral indicators.

Table 5

Correlations between measures (raw scores).

Measure	Box commission errors	Word commission errors
1. Global Executive Composite (BRIEF)	.610***	.198
2. Metacognition (BRIEF)	.573*	.238
3. Behavioral Regulation (BRIEF)	.616***	.079
4. Inhibit (BRIEF)	.676***	.251
5. ADHD (CBCL)	.636***	.128
6. Rule-Breaking Behavior (CBCL)	.407*	-.053
7. Somatic Complaints (CBCL)	.036	.057
8. Tower – 1st Move Time	-.356	.226
9. Tower – Total Rule Violation	.516*	.254
10. TMT – Condition 4 – Time	.050	.331
11. TMT – Condition 4 – Errors	.010	.147
12. VF – Condition 1 – Errors	-.210	-.074
13. CWIT – Condition 1 – Errors	.074	.140
14. CWIT – Condition 3 – Time	.359*	.590***
15. CWIT – Condition 3 – Errors	.393*	.373*
16. TQ – Abstraction Score	-.310	.115

* $p < .05$.
*** $p < .001$.

3.2. Predictors of everyday executive functioning

Multiple regression (Tables 6 and 7) using raw scores was used to determine the ability of the two Stroop measures (D-KEFS CWIT, condition 3, total errors/VR-Stroop task, box condition, commission errors) to predict everyday executive functions as measured by the BRIEF and CBCL questionnaires: [1] BRI, [2] MI, [3] Inhibit scale, [4] GEC, [5] RBB and [6] ADHD scale. Producing more commission errors in the VR-Stroop task was significantly associated with greater deficits in behavioral regulation (BRI; $\beta = .75$, SE = .18, $t = 4.66$, $p < .001$), metacognition (MI; $\beta = .72$, SE = .37, $t = 4.43$, $p < .001$), inhibition (Inhibit scale; $\beta = .83$, SE = .06, $t = 5.81$, $p < .001$), global executive functioning (GEC; $\beta = .77$, SE = .52, $t = 4.84$, $p < .001$), rule breaking (RBB; $\beta = .44$, SE = .05, $t = 2.47$, $p = .02$) and attention (ADHD scale; $\beta = .82$, SE = .06, $t = 5.57$, $p < .001$). The number of commission errors in the VR-Stroop task (box condition) explained a significant proportion of the variance on four scales from the BRIEF (55% inhibition, 45% behavioral regulation, 42% metacognition, 47% global executive composite) and two subscales from the CBCL (15% rule-breaking behavior and 54% attentional deficits). Results on the CWIT did not significantly predict any of the results on subscales from the BRIEF or CBCL ($p > .05$).

Table 6

Predictors of indirect indicator of executive functioning (CBCL).

Predictor	Scores on the ADHD problems scale		Scores on the rule-breaking behavior scale	
	ΔR^2	β	ΔR^2	β
Step 1	.000		.193*	
Control variables		.352*		.628*
Step 2	.001		.007	
CWIT errors		-.122		.031
Step 3	.544***		.152*	
VR (Box) commission errors		.823***		.435*
Total R^2	.545***		.352*	
n	30		30	

[a] Control variable includes age.
* $p < .05$.
*** $p < .001$.

Table 7

Predictors of everyday executive functioning (BRIEF).

Predictor	Inhibit		Metacognition		Behavioral Regulation		Global executive composite	
	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	.016		.011		.012		.001	
Control variables		.480*		.196		.423*		.285
Step 2	.007		.001		.000		.001	
CWIT errors		-.160		-.123		-.091		-.117
Step 3	.552***		.424***		.451***		.473***	
VR (box) commission errors		.830***		.727***		.750***		.768***
Total R^2	.719***		.437***		.463***		.475***	
n	30		30		30		30	

[a] Control variable includes age
* $p < .05$.
*** $p < .001$.

3.3. Predictors of performance on the VR-Stroop task

Multiple regression (Table 8) using raw scores was also used to determine the ability of three D-KEFS measures (1) CWIT (condition 3) commission errors, (2) TMT total errors and (3) TT total rule violation to predict the number of commission errors on the VR-Stroop task (box condition). The results indicate that, taken together, only having a higher number of rule violations on the D-KEFS TT ($\beta = .52$, SE = 1.54, $t = 3.63$, $p = .001$) was significantly associated with a higher number of commission errors in the VR-Stroop task, explaining 21% of the variability in performance. When attempting to predict the number of commission errors in the word condition with the same three paper–pencil EF measures (Table 8), only having a higher number of commission errors in the CWIT (condition 3; $\beta = .35$, SE = 0.75, $t = 2.48$, $p = .02$.) was significantly associated with a higher number of commission errors in the VR-Stroop task, explaining 12% of the variance in performance.

Table 8

Predictors of performance on the VR Stroop task.

Predictor	Commission errors (box)		Commission errors (word)	
	ΔR^2	β	ΔR^2	β
Step 1	.208*		.199*	
Control variables		-.518*		-.484*
Step 2	.000		.026	
TMT errors		.079		.161
Step 3	.210*		.053	
TT rule violation		.518		.307*
Step 4	.044		.120*	
CWIT errors		.216		.353*
Total R^2	.463*		.398*	
n	34		36	

[a] Control variable includes age
* $p < 0.05$.

4. Discussion

The first aim of this study was to determine which traditional paper–pencil EF tests are associated with performance on the VR-Stroop task. As expected, the results indicate that performance on the VR-Stroop task is associated with a more traditional Stroop measure of inhibition (D-KEFS CWIT). This strong association supports the construct validity of the task. The results are consistent with a previous study, which demonstrated that VR-CPT memory measures only correlate with scores on traditional memory measures (Parsons et al., 2007). These results can be added to existing data supporting the construct validity of cognitive VR tasks (Parsons et al., 2008; Rand et al., 2009).

In the present study, the number of rule violations on the D-KEFS TT and commission errors on the D-KEFS CWIT, both measures of an individual's capacity to follow instructions and inhibiting appropriate responses, explained performances on the box and word conditions of the VR-Stroop task. The similarity between the impulsivity control required in the word condition of the VR-Stroop task and the traditional paper–pencil Stroop test (CWIT) could logically explain such an association. The TT and the box condition of the VR-Stroop task also evaluate inhibitory skills, but focus on motor inhibition rather than on verbal abilities, which could explain the relationship between results on these tasks. These associations suggest that in addition to measuring the same inhibition construct as the traditional paper–pencil Stroop test, the VR-Stroop task also approximates inhibition components found in other established EF measures and therefore reinforces the construct validity of the task. No association was found between performance on condition 1 of the CWIT and the VR-Stroop task. This lack of correlation could be explained by the low rate of errors ($M = .35$, SD = .68) on the CWIT task.

A main objective of neuropsychological assessment is to predict a person's level of functioning in everyday life. The second goal of this study was therefore to compare paper–pencil EF tests and the VR-Stroop task in their ability to predict everyday executive functioning and behavior, as measured by validated, standardized questionnaires. Performance on the VR-Stroop box condition was strongly associated with cognitive components of daily executive functioning and with externalizing behavior, whereas the VR-Stroop word condition did not correlated with any parent rating of EF or behavior. This lack of association, although somewhat surprising, could be explained by the higher level of EF regulation required in the word condition. Indeed, it seems that the relatively short interstimulus interval used in both conditions combined with the higher level of difficulty of the word task may tax EF abilities at a level beyond the EF regulation required in the everyday situations presented in the questionnaires. Adjustment of the inter-stimulus interval in the VR task should therefore be of special concern to researchers, and changes in the presentation pace could be considered to modulate task difficulty.

Although performance on the VR-Stroop box condition was associated with a number of components on the BRIEF and CBCL, this relationship was not universal; rather it was specific to scales relevant to EF. For example, no correlation was found between the VR-Stroop task and Somatic Complaints (CBCL). This finding supports the ability of the VR-Stroop task to provide a specific estimate of EF in everyday behavior. In both questionnaires, parents' perceptions of their child's inhibitory skills (scores on the BRIEF Inhibit scale and the CBCL ADHD scale) were the most associated with direct measures of inhibition, assessed with the VR-Stroopbox condition. These results are consistent with previous studies that demonstrate similar results between parent-based questionnaires and performance on the VR-CPT, indicating that VR could be an effective way to ecologically test cognitive function (Moreau, 2006; Parsons et al., 2007). VR appears to be a strong predictor of everyday life executive functioning and behavior as shown by its ability to explain outcome on well-recognized scales of behavioral EF and externalizing behavior, while a similar paper–pencil EF test (D-KEFS CWIT) failed to predict the same outcomes. These results support the idea that VR does not only look like the real world, it also includes demands that require real world functional abilities. The potential of VR as an ecological assessment tool, shown in this study, is consistent with prior propositions suggesting the utility of virtually enriched environments as a novel and effective way to ecologically test cognitive function (Parsons et al., 2007; Rizzo et al., 2004). Traditional neuropsychological tools used in controlled contexts can provide adequate information on cognitive functioning, but VR may offer a possibility for direct evaluation of cognitive functioning in dynamic representative real word paradigms and has the potential to predict how cognitive difficulties are reflected in daily situations. VR could thus be seen as a complementary ecological technique to traditional tests in the assessment of complex cognitive abilities.

Additionally, VR technology seems to enhance participant enjoyment leading to increased motivation (Rizzo et al., 2004). The use of VR appears to reduce motivation problems and ceiling effects reported in paper–pencil cognitive tests (Rizzo et al., 2004;Schultheis et al., 2002). Examiners could benefit from enhancement of motivation particularly when assessing adolescents who generally understand technology and are sensitive to its appeal (Nemire et al., 1999). Increased motivation and engagement in the assessment of fundamental cognitive skills in adolescents could further enhance the sensitivity of such measures to real life aptitudes, impacting positively on the ecological validity of test score interpretations. Though it may as yet be unrealistic to propose the use of VR in standard clinical practice, sustained progress in VR technology, along with cost reductions, are bringing about the development of more valuable, usable and accessible VR systems (Schultheis et al., 2002). The increasing availability and affordability of VR offers new possibilities for novel ecological neuropsychological assessment. VR has already found many applications as a psychotherapeutic tool in various domains such as post-traumatic stress disorder, social anxiety, traumatic brain injury, phobia, eating disorders and obesity (Riva, 2005; Rothbaum et al., 2001; Zhang et al., 2003).

The use of VR as a complementary assessment tool may overcome concerns regarding the predictive value of paper–pencil EF tests for everyday life and concerns regarding methodological limitations of questionnaires, including indirect assessment of an individual's capabilities, parental/third party bias when completed by an adult caregiver (Najman et al., 2001; Richman et al., 1999), and social desirability bias when completed as a self-report (Nederhof, 1985; Richman et al., 1999).

4.1. Limitations

There are some limitations that need to be acknowledged regarding the present study. First, participants were mainly Caucasian and had similar socio-demographic characteristics, somewhat limiting the generalization of results. Second, our sample, recruited on a voluntary basis, may not be representative of the entire adolescent population. A further study including different socio-demographic backgrounds and different ethnic groups is therefore suggested. Third, the BRIEF and CBCL were designed to identify behavioral problems and may not be sensitive to the full range of normative and aberrant behaviors. They are therefore not ideal measures for healthy adolescents, who are unlikely to experience significant problems in everyday behavior. There are currently few standardized behavioral measures of EF available, which inevitably restricts the possible choices of measures and justifies the use of the CBCL, which is nevertheless a well established, standardized and validated everyday behavioral measure, with close links to EF. Finally, future research using a clinical group would be of interest to examine if the VR-Stroop task can be used to identify EF problems and to explore the sensitivity and specificity of the task. Longitudinal studies would also be of interest to examine the ability of the VR-Stroop task to predict future functioning.

5. Conclusions

In this study, performance on a VR-Stroop-like task of inhibition correlated with more traditional forms (paper–pencil and parent questionnaires) of EF assessment, but VR performance more accurately reflected everyday behavioral EF. The evidence that paper–pencil EF tests do not accurately reflect everyday EF and behavior when compared to VR suggests that VR could be a useful complementary technique for the ecological assessment of high-order cognitive abilities. The strength of VR lies in its capacity to make participants feel like they are 'present' in the environment and to simulate naturalistic situations and demands in order to reflect real life functioning and therefore enhance the ecological validity of test score interpretations. VR technology also allows absolute control over stimulus presentation and precise response measurement. Given the novelty of VR as a cognitive assessment tool, it is important to continue to conduct research on its association with more traditional neuropsychological measures in order to confirm such propositions. Nevertheless, VR assessment appears to be an interesting direction for more ecological and enjoyable measurement of fundamental cognitive skills.

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Chapter 5
Discussion

The main objectives of this thesis were twofold: 1) to explore the conception of impulsivity in neuropsychology and propose a conceptualization that reflects the complexity and diversity of this concept; and 2) to propose a novel approach to assess impulsivity with VR. The next sections will summarize the results of each article and evaluate them in the light of recent findings. An integrated discussion will follow. The findings of the current thesis will be put into their respective contribution to the field of impulsivity, VR research, and general neuropsychology. Suggestions for forthcoming research will also be drawn. In particular, potential improvements for the VR-Stroop task will be suggested.

Article 1: Main findings

The goal of the first article (Chapter 2) was to propose a conceptual and operational definition of impulsivity. An exhaustive and critical description of the currently available definitions and instruments was provided. This article proposed a conceptualization of impulsivity which divides it into five factors: 1) motor impulsivity; 2) poor ability to stop; 3) attentional impulsivity, cognitive impulsivity or poor perseverance; 4) seeking immediate gratification; and 5) sensation-seeking, risk-taking, carelessness or low sensitivity to consequences. Therefore, impulsivity should be referred to as impulsivities, outlying the various components of this construct. A recent study by Caswell et al. (2013) supports this evidence.

As it was stressed in this article, the assessment of impulsivity remains a challenging task for which no complete and versatile instrument exists. Traditionally, questionnaires were the instrument of choice. However, conclusions drawn from such questionnaires do not represent adequately the patient's functioning, especially in clinical populations (Clark, Robbins, Ersche, & Sahakian, 2006; Lansbergen, Schutter, & Kenemans, 2007; Wingrove & Bond, 1997). Such assessments are also not suited for individuals that are very impulsive (Goldstein & McNeil, 2013) or detained in a correctional institution.

Even if impulsivity is widely accepted as a multidimensional construct (Evenden, 1999), it was also outlined that the great majority of existing studies used only one test to assess it. Additionally, the conceptualizations of impulsivity are often made in pair with an instrument (Dodrill, 1997; Parsons, Rizzo, & Buckwalter, 2004). By doing so, the construct is linked to a specific component of impulsivity, which is measured by the instrument (e.g. Logan & Cowan, 1984; Verbruggen & Logan, 2008; Verbruggen, Logan, & Stevens, 2008). This could partly explain why so many explanatory models exist and why generalization between concepts is a challenging task. A meta-analysis (Van Mourik, Oosterlaan, & Sergeant, 2005) came to the conclusion that traditional neuropsychology tasks should not be used to assess impulsivity on their own, because they show weak relationships with impulsivity constructs. Their predictive validity is, however, greatly increased when they are administered with other impulsivity tasks and the combined predictive value is used or when various components of impulsivity are addressed at the same time (Perugini, Harvey, Lovejoy, Sandstrom, & Webb, 2000).

This article concluded by proposing VR as a novel approach to assess multiple types of impulsivity simultaneously. Therefore, this was the focus of the next two articles.

Article 2: Main findings

Being one of the most popular measures of inhibition for adults (Lezak et al., 2012), the Stroop was used here. However, the Stroop in itself only has weak correlations with other inhibition components (Heflin et al., 2011), so it was adapted and integrated in the VRe. This environment, the ClinicaVR: Apartment – Stroop (VR-Stroop) depicts a living room with distractions that are close to everyday living of adult populations (ex.: a cellphone ringing).

First, for this experiment, the VR-Stroop results correlated significantly with those of inhibition related tasks. Furthermore, the VR task was significantly associated with typical assessment measures of different components of impulsivity. More specifically, the VR-Stroop was able to assess the following three components of impulsivity: motor, poor ability to stop an ongoing action and attentional impulsivity. This suggests that this virtual task allows assessing aspects of cognitive and motor inhibition, in less than 10 minutes. This is a great advantage as most inhibition measures (the T.O.V.A. for example) require up to 20 minutes per evaluation. They are also unable to assess multiple facets of impulsivity simultaneously. The VR-Stroop showed construct validity with traditional measures of inhibition, which supports the construct validity of cognitive tasks redesigned in VR (Parsons et al., 2007, 2015; Parsons & Rizzo, 2008a, 2008b; Rand et al., 2009).

A secondary objective of this experiment was to explore if the VR-Stroop was capable of eliciting a Stroop-effect. This virtual task is based on a bimodal presentation (auditory and visual), whereas the traditional Stroop relies on a visual presentation only. In the traditional Stroop, the first two conditions (color naming or word reading) are rather easy and are associated with fast response times. The inhibition condition (naming the color in which the word is printed) is harder and associated with longer response times, especially for items that are dissimilar (ex.: blue written in red). The task creates a cognitive dissonance between reading automatization and naming a color. This is responsible for lengthier reaction times in the inhibition condition (see Parsons et al., 2015). Doing this also gets harder with age (Verhaeghen & De Meersman, 1998; West & Alain, 2000). For the VR-Stroop task, a color word is showed in a different (or not) ink color. Simultaneously, a color is heard through the speakers. The participant must click the mouse when the color of the ink and the color heard match. Some of the trials are easier than others. This is the case for congruent trials, where the color word matches the ink ("red" written in red). It is rather easy here to respond quickly if the word "red" is heard. Incongruent trials are represented by a different color name and ink (ex.: "blue" written in a green color). These trials were thought to be harder and it was expected that they would require more time to answer. This was the case as an internal interference effect was observed between congruent and incongruent trials. Participants needed more time for incongruent trials. Similar results were also found by Parsons and colleagues with a comparable task (Parsons et al., 2011). These findings support that a Stroop-effect can be elicited with the VR-Stroop.

This article also had a third objective to evaluate the task parameters, more specifically the presentation rate of stimuli. The results from the pilot phase showed that the task was too easy when the interstimuli interval (ISI) was at 2000ms. A ceiling effect was observed. When the ISI between stimuli was shorter, the sensitivity of the task greatly improved. It was then concluded that the optimal ISI would be 1000ms. This was the ISI also used for the previous experiment (Chapter 3). To our knowledge, the 2000ms ISI in the VR-Stroop is only used for research done with elderly or demented patients as they required more processing time (Nolin & Boucher, 2011).

Lastly, it was observed that the VR-Stroop was associated with a good sense of presence and low occurrence, count and intensity of cybersicknesses. As discussed in the first chapter, these are critical prerequisites for any VR task to become a widely used assessment. In other words, this further indicates the superb potential of the VR-Stroop.

Given the validity of the virtual Stroop with adults, the last article focused on using this task with another population to see if similar results could be obtained. This was addressed in the next article as the VR-Stroop was used with adolescents.

Article 3: Main findings

This article aimed at comparing the performances obtained on the VR task with traditional measures. This was done to assess the task's validity and sensitivity as a measure of impulsivity. It was expected that the VR-Stroop would show similar results to the traditional assessment of impulsivity. A second objective was to compare the predictive abilities of the ClinicaVR: Classroom – Stroop (VR-Stroop) for everyday functioning with those of traditional paper-pencil tasks. Because the apartment setting used in the previous experiment is not close to the daily routine of adolescents, this could negatively influence sense of presence in participants (as seen in Chapter 1). Consequently, the VR-Stroop was projected in a virtual classroom. This classroom has been validated on many occasions and with different clientele (Adams et al., 2009; Bioulac et al., 2012; Moreau et al., 2006; Nolin et al., 2009, 2011, 2012; Nolin, Stipanicic et al., 2013; Parsons et al., 2007; Rizzo et al., 2006). The results from the previous article outlined that the VR-Stroop was capable of assessing multiple forms of impulsivity. Similar results were expected with this experiment.

As expected, the VR-Stroop proved to be a valid and sensitive task measuring impulsivity. Specifically, commission errors on the VR task were associated with components of impulsivity outlined by traditional measures (e.g. Trail-Making Test, traditional Stroop and Tower Task). Furthermore, individuals showing quick response times were more likely to break the rule when completing the Tower Task, which is also a measure of poor inhibition. Lastly, omission errors in Condition 1 (color blocks) of the VR task were significantly associated with longer completion time in the traditional Stroop, again pointing towards impulsivity.

These results are promising for the VR-Stroop, as it seems to assess multiple components of impulsivity (poor inhibition, motor and cognitive impulsivity) simultaneously. This is consistent with previous studies that also pointed to VR as a reliable assessment when compared to traditional measures (Martin & Nolin, 2009; Mitchell et al., 2007; Moreau et al., 2006; Nolin et al., 2009, 2012; Parsons et al., 2011, 2015; Pollak et al., 2009). Condition 1 (color blocks) seems, however, to have more sensitivity than Condition 2 (color words). It could be hypothesized that Condition 1 is already demanding and could be used on its own. This will be explored in the general discussion.

The second objective of this article was to understand the relationship between performances on the VR-Stroop and everyday functioning. Performances on the VR task were more accurately associated with behavioural questionnaires than the traditional paper-pencil Stroop task. This further supports the increased predictive validity of VR, as it was outlined in Chapter 1 of this thesis. This VR task was also associated with good predictive value of behavioural components of inhibition, which indicate that the VR-Stroop (both ClinicaVR: Apartment-Stroop and ClinicaVR: Classroom - Stroop) is ecological.

In summary, the VR-Stroop is a short and safe (few cybersickness) assessment to evaluate impulsivity in both adolescents and adults. Second, it has the potential to evaluate a broader spectrum of impulsivity components than traditional tasks (which usually only assess one component at a time). Thus, the bimodal VR-Stroop seems capable of measuring internal interference control and motor inhibition simultaneously. The VR-Stroop is an ecologically valid assessment option that can provide a rigorous control of distractors presentation, stimuli intervals, precise measurements of responses and reaction times (Parsons et al., 2015). More research is, however, needed to see how it would perform with clinical populations. More on this will be addressed in the general discussion.

Overall thesis discussion

In this section, the goals of this thesis will be reviewed and the findings will be put into perspective. Suggestions will be made to address limitations, along with proposals for new research.

The main objectives of this thesis were twofold. First, the definition of impulsivity was explored and a conceptualization that reflects the complexity and diversity of this concept was proposed. Second, a task to assess impulsivity with VR was developed. These objectives were successfully met. The main findings of this thesis revealed that: 1) Impulsivity is a complex and multidimensional construct; 2) No assessment options are currently available to evaluate more than one component simultaneously; 3) Virtual reality is a technology capable to assess various components of impulsivity; 4) The VR-Stroop is an easy, quick, reliable and complete tool to assess inhibition in both adolescents and adults; 5) The VR-Stroop is an ecologically valid assessment of impulsivity. Next, the assessment of impulsivity and the use of VR in this assessment will be discussed in details.

Assessment of impulsivity

The role and core of neuropsychology evolved greatly in the past years. Neuropsychologists are more involved than before in clinical settings and are not confined to rehabilitation centers anymore. A shift was made from deficit measurement (function-based assessment) to an approach based more on functional competence (or function-led assessment) (Chelune & Moehle, 1986). Unfortunately, the assessments used by neuropsychologists did not completely follow this transition accordingly. This leaves neuropsychologists with the difficult task to assess individuals and predict their behaviours based on measures that are not always representative. The most difficult task lies with the clinicians and researchers, as they have to choose the assessment to use according to what they want to evaluate. Furthermore, these professionals are often reluctant to change assessment tasks in their practice (Botella, 2005).

This thesis demonstrated that impulsivity is a multidimensional construct. Different tasks assess different components of impulsivity. It is therefore difficult to assess multiple components at once, as no measure is currently available to do so. The former conception that only two types of impulsivity are concurrent (motor vs. cognitive) is now out-dated. It is proposed here that impulsivity should be referred to as impulsivities, to better represent the diverse factors of this construct. Impulsivity was here defined as: 1) motor impulsivity; 2) poor ability to stop; 3) attentional impulsivity, cognitive impulsivity or poor perseverance; 4) seeking immediate gratification; and 5) sensation-seeking, risk-taking, carelessness or low sensitivity to consequences. This definition was obtained by combining the similarities and differences of each current conceptualization.

One limitation with the definition proposed in this thesis is that it relies solely on semantics and previous conceptualizations. Subsequent validation is here needed. This could, however, be problematic as components are not always compatible on a structural or conceptual base. As seen in Chapters 1 and 2, the factors are also known to not highly correlate with each other. It is unclear whether the semantic concept of impulsivity really refers to a single feature, state or trait. Most likely this is not the case, particularly as components can be tested with a high reliability. For the further understanding of impulsivity, it would be desirable to find underlining neurophysiological or neurobiological bases.

To do so, the different components of impulsivity would have to be investigated on a neurophysiological level (e.g., EEG). Involved networks would have to be identified and functional responses would have to be explained. Then, findings across the components would have to be compared. Certainly, further researches are needed.

The ClinicaVR Suite

Results from this thesis point to a general ecological validity of the virtual Stroop. Similar results were also found using the same tasks in various populations. The Stroop task used in this thesis is part of an assessment package that can be obtained by Digital Media Works (DMW): the DMW ClinicaVR™ Suite. Included in this evaluation suite are the classroom and the apartment environments used in this thesis. The examiner can then choose between the Stroop task or a VIGIL-CPT. Similar to what was done in this thesis, the traditional VIGIL-CPT was adapted to fit the VRe. These possible four combination of assessments provided in the DMW ClinicaVR™ Suite (ex.: CPT in the apartment, Stroop in the classroom) give great flexibility for researchers to address impulsivity or attention in children from seven years of age to elders.

These tasks were validated and, similar to the results obtained in this thesis, showed great ecological validity (Nolin & Boucher, 2011; Nolin et al., 2012). Furthermore, the tasks were also used with clinical populations like traumatic brain injury (Martin & Nolin, 2009), elders (Nolin, Banville et al., 2013; Nolin & Boucher, 2011) and autism (Pierre & Stipanicic, 2012). These tasks are also able to detect subtle deficits in sport concussions, as it was shown by Nolin and colleagues (2012). In this experiment, overall, performances on the traditional CPT did not differ between groups (concussion vs. control), but the VR-CPT was more sensitive to detect subtle deficits in attention and inhibition in adolescents with a prior sport concussion. These participants were more impulsive and less focussed on the VR task, when compared to the control group. Adolescents with a prior concussion made significantly more commission errors. They also had a higher number of head movements than the control group and these head movements increased over time. These results are consistent with recent findings pointing to long-term repercussions of sport concussions (Barlow, 2014; De Beaumont, Beauchemin, Beaulieu, & Jolicoeur, 2013; Keightley et al., 2014; Tremblay et al., 2014).

The VR-Stroop from the DWM Suite also showed greater sensitivity than traditional assessments while keeping great psychometric properties in various experiments (Henry et al., 2013a, 2013b; Henry, Joyal, Drouin-Germain et al., 2012; Henry, Joyal, & Nolin, 2012; Henry, Nolin, Drouin-Germain et al., 2011; Henry, Nolin, & Joyal, 2011, 2014; Henry, Nolin, Joyal et al., 2011; Lalonde et al., 2012, 2013; Nolin et al., 2009, 2011, 2012; Nolin, Stipanicic et al., 2013; Stipanicic et al., 2011). These results are promising for the DMW ClinicaVR™ Suite.

VR-Stroop and impulsivity assessment

As part of this thesis, the VR-Stroop was developed. It was shown that using the VR-Stroop to assess impulsivities leads to greater assessment sensitivity and better predictive value. This was not achieved by any other measures so far. It can be concluded that the second goal of this thesis was reached. However, there were some limitations found, and in the course of applying the VR-Stroop, further potential improvements became obvious. Next, potential criticism and improvements to the VR-Stroop task will be addressed.

Computerized traditional assessments. An opinion frequently encountered is that VR is just a computerized version of traditional task. Conclusions from this thesis strongly oppose this view. Many traditional assessments were indeed digitalized in the past years and are easily accessible online (see the large library of Inquisit™ for example: www.millisecond.com). A task based on the Stroop was also computerized in recent years. The Automated Neuropsychological Assessment Metrics (ANAM), was developed by Johnson and colleagues (Johnson, Vincent, Johnson, Gilliland, & Schlegel, 2008). While this task resembles and is correlated to the traditional Stroop task (Reeves, Winter, Bleiberg, & Kane, 2007), it does not immerse the participant in an environment with proximal and contextual cues. It is also not possible to increase or decrease the difficulty of the task, which is essential to study arousal more closely. According to Parsons and colleagues, it is fundamental to be able to manipulate arousal in computerized tasks to better understand automatic from intentional processes (Parsons et al., 2015).

With VR, it is rather easy to achieve greater levels of complexity. The use of distractors is a good example. In the VRe proposed in this thesis, participants were surrounded by auditory, visual and combined distractors. These distractors would typically be present in a real classroom (other classmates, bell, traffic outside) or in a real apartment (cellphone ringing, vacuum, other people in the house). Distractors are associated with a greater complexity and hence provide a scenario closer to a real-life situation. This should lead to higher predictive value of the participant's behaviours (Parsons et al., 2015).

In summary, traditional (typically paper-pencil) tasks were computerized and adapted for computers in the past decades. However, the results and conclusions that can be drawn from them are not comparable with what VR has to offer.

Randomization of distractors. While the task in its present form was sufficient for the goals of this thesis, it can most likely be improved by considering the features of the distractors. As seen before, distractors are associated with better predictive outcome and sense of presence. However, the influence of their sequence, choice, placement and nature on the task is not yet systematically investigated. This was the case in this thesis.

Distractors were here placed in the VRes to resemble a real-life scenario. The order in which the distractors were presented was not randomized, which limits the conclusions that can be drawn here. In other words, all tasks used in this thesis had fixed scenarios. This means that distractors followed each other in the same sequence. Typically here, a scenario is a two-minute-long sequence that is repeated three times during the tasks. While helping understand performances across time and participants by keeping the sequence the same, this limits the conclusions that can be drawn about the different distractors. For research purposes, it would be favourable to use a random sequence that helps disentangle the effect of specific distractors from the effect of their presentation time. This would allow drawing conclusions like participants get more or less distracted over time. Currently, this is not possible with the configuration of the task as certain distractors appear at a fixed time. The distractors were however similar for both the classroom and the apartment. For example, an auditory distractor was presented in the first five seconds of the task. For adults, a jackhammer could be heard, whereas a bell could be heard in the classroom.

Some stimuli seemed to be better than others at distracting participants in the VR-Stroop. When adults were asked on a qualitative level which stimuli was the most distracting, the vast majority of participants answered the iPhone. Some participants however argued that it was too distracting, as they were unable to do anything while this virtual phone was ringing. Others distractors (ex.: sound of the airplane) were not acknowledge by all adult participants (Henry, Nolin, Joyal et al., 2011). This indicates that the capability of the stimuli to distract participant covered the desired range of intensity (from low to high). However, this was not systematically investigated across all experiments and participants. This is a potential fruitful avenue for further improving the VR-Stroop.

In summary, further research should alternate the sequence and frequency of distractors. By doing so, each distractor's power could be better detailed. Their influence across time could also be understood as well as their stability in distracting participants over time.

Configuration of the task. Another improvement of the VR-Stroop lies in the configuration of the task. In Chapter 3, the Condition 2 (color words) was less correlated with inhibition measures than Condition 1 (color blocks). Condition 2 also had less predictive value. Similar results were also found in Chapter 4. This is rather surprising, as the color words condition (Condition 2) of the VR-Stroop was inspired by the Condition 3 of the traditional Stroop. This task assesses cognitive inhibition.

A potential explanation for this finding is that the VR-Stroop is harder (or more arousing) than typical impulsivity measure, and hence cannot be associated with what is usually measured with traditional assessments. This would mean that the Condition 1 of the VR-Stroop is difficult to a level that is comparable to the condition 3 of the traditional Stroop.

A general sequence effect could also be possible, as the harder condition was always presented second in the VR experiment. Further research should see if similar results are observed when the conditions are counter-balanced. The distractibility potential of the stimuli could also be diminished in Condition 2, as they were the same as in Condition 1. Participants could therefore become used to the distractors and their distractibility strengths would be greatly diminished over time. If participants grow used to a distractor, the second condition could become easier, even if the task in itself is more difficult to accomplish.

Another hypothesis could be that the pace of the task was too quick or the first task was too hard. This could lead participants to experience a form of ego-depletion. When a task is cognitively too demanding, the following task cannot be successfully achieved (Webb & Sheeran, 2003). This refers to ego-depletion and is induced with a thought-suppression task such as the White-Bear Task (Wegner, Schneider, Carter, & White, 1987) or the Stroop. Ego-depletion does not seem, however, to be involved for the findings of this thesis, as performances were not significantly altered over time and stayed constant in Condition 2 (Henry, Joyal, Drouin-Germain et al., 2012, Henry et al., 2013a, 2013b; Henry, Nolin, Drouin-Germain et al., 2011; Henry, Nolin, & Joyal, 2011, 2014; Henry, Nolin, Joyal et al., 2011; Lalonde et al., 2012, 2013). Also, the task parameters were investigated in Chapter 3. Nevertheless, subsequent research should investigate this hypothesis further.

To answer the limitations exposed here, conditions of the VR-Stroop should be counter-balanced. For now, it could be suggested that Condition 1 is sufficient to assess inhibition on its own. Furthermore, the first condition seems hard enough and sensitive enough to generate valid and representative conclusions. Since there is no real added value in Condition 2, its use is questioned. Further research should focus on its contribution to the assessment of impulsivity in normal adults or teenagers.

The role of attention

Another criticism that could be made on the VR-Stroop is that it does not only assess impulsivity. The VR-Stroop was significantly correlated with inhibition measures. However, significant correlations were also found for attentional measures.

The definition of impulsivity provided in this thesis includes the aspect of cognitive inhibition (component 3). This refers to the capacity to resist external and internal interference. Resisting internal and external interference is also linked to higher levels of attention. This can be the case for sustained attention (see Barkley, 1997, 2014). It is documented that impulsivity is closely related to attentional control, vigilance, executive functions and even working memory (Ellingson, Fleming, Vergés, Bartholow, & Sher, 2014; Radvansky & Copeland, 2001).

As sustained attention is part of the definition of a component of impulsivity proposed here, the correlations observed would be expected. It would be desirable if the different facets of inhibition could be disentangled from the role that concepts of attention play in them. There are well-researched concepts of attention, which include proposed neuronal circuitry and methods to test them. For example, see the Attentional Network Test from Fan and colleagues (Fan, McCandliss, Sommer, Raz, & Posner, 2002). This is another avenue that could be explored with future research where neuronal background of impulsivity would be explored.

As seen above, although the VR-Stroop is associated with superior predictability and correlations than traditional tasks, it still needs further exploration. It was still, however, able to address the objectives of the current thesis. Next, further discussion points will be addressed in regards of the task and about VR in general.

Further recommendations

Additional discussion aspects will be explored in this section. The topics addressed here are outside the objectives of this thesis, but were outlined throughout the experiments. The framework used as part of this thesis is very similar to many of the VR experiments and hence some of the next tips could be applicable to VR research in general. Suggestions and improvements will also be outlined.

Variables in VR

While there is a large body of literature about the importance of sense of presence, immersion and cybersickness, few articles report those measures as part of their experiments in the past years. Leading authors such as Parsons, Rizzo or Riva all mention the importance of these constructs in their literature review, but such variables are not measured in their research design or articles (Parsons et al., 2015; Riva, 2005; Rizzo et al., 2004; Schultheis & Rizzo, 2001).

As it was outlined in Chapter 1, cybersicknesses can negatively influence performances on a VR task. Recent studies found that cybersickness is statistically different between clinical and control group. This was the case for the experiment from Nolin and colleagues who used the same classroom environment from this thesis (Nolin et al., 2012). Sport concussions and control adolescents were assessed with a virtual CPT (the ClinicaVR: Classroom – CPT). Adolescents with a history of sport concussion had significantly more cybersickness than the control group. It could be argued that cybersickness provides a dependent variable or a test in its own rights.

Participants of this thesis had very few to no cybersickness symptoms. This suggests that the environments used induced low levels of discomfort. Also, the few symptoms did not influence performances negatively. This further supports the use of cybersickness to differentiate between control and clinical populations. More studies on this are warranted.

Another fundamental variable of VR is sense of presence. It is also known that sense of presence is linked to how engaged in a task a participant is. Sense of presence in virtual psychotherapy is thought to be an important and main contributing factor (Slater & Wilbur, 1997). It is debated whether sense of presence is also a critical variable for assessment (e.g. Drouin-Germain et al., 2012). This seems to be supported by the findings from the VR-Stroop, as there were no correlations between sense of presence and task performances. Sense of presence was not associated with better cognitive performances in experiments of this thesis (Henry et al., 2013, 2014). This is also supported by others (Slater, Linakis, Usoh, Kooper, & Street, 1996). It seems that sense of presence does not seem to be an essential factor in VR assessment (Banville, Nolin, Lalonde, Henry, & Déry, 2008; Drouin-Germain et al., 2012).

Furthermore, ecological validity is important when working with VR. Few studies however report their results in terms of veridicality or verisimilitude. This could mean that the tasks could not be as ecologically valid as the authors claimed. Nevertheless, if this would be the case, they would still arguably offer a broader and more complete picture, while being more sensitive than traditional measures.

The VR-Stroop seems to include components of veridicality. This VR task is based on a widely recognized impulsivity measure and was shown to have a Stroop-effect. This task also shows representativeness (see Burgess et al., 2006). Furthermore, the performances obtained were closely linked to questionnaires of observed behaviours in adolescents. This point to a good predictive value (veridicality).

Discriminant validation

This thesis showed that the VR-Stroop was significantly correlated with traditional measures of impulsivities. This refers to concordant validity, where a test is correlated to a similar task. Another criterion would be to know if the VR-Stroop could demonstrate discriminant validity. The VR-Stroop assesses the following three components of impulsivity as defined in this thesis: motor (component 1), poor ability to stop an ongoing action (component 2) and attentional impulsivity (component 3). The VR-Stroop should therefore be compared to tasks of other impulsivity components to see if it differs from them.

One component not assessed by the VR-Stroop is component 5 of the definition provided in this thesis; sensation seeking and risk-taking behaviours. Because of its framework, the VR-Stroop should not be associated with such tasks. Risk-taking behaviors implicate different constructs than in stopping an ongoing action or attentional impulsivity. Risk-taking behaviours are usually associated with personality traits (greed for example), which are factors that can contribute to impulsivity (Balot, 2001; Eek & Biel, 2003). Preliminary results support this hypothesis (Henry et al., 2013, 2014). However, risk-taking is only semantically linked to impulsivity in this thesis. The neurological processes underlining the components of impulsivity as assessed by the VR-Stroop are still unknown. Neurophysiological measures could hence help further disentangle the processes.

Impulsivity questionnaires

Subsequent research should also focus on comparing results obtained on the VR-Stroop with results from impulsivity questionnaires. Given the limitations outlined about questionnaires in Chapter 2 (e.g. they do not assess the same construct and are not sensitive), it would be expected that the VR-Stroop should not be significantly correlated to such reported measures of impulsivity. Preliminary results investigating the adult VR-Stroop with the BIS-11 support this hypothesis (Henry et al., 2013, 2014). The VR-Stroop was not significantly correlated to any of the main components or sub-scales of the BIS-11.

It is interesting to note that different results were however obtained in Chapter 4. Performances on the VR-Stroop were associated with behavioural questionnaires. If these findings are replicated in future research, they could be explained, in some parts, by the nature of these questionnaires. Typically, items used in adolescents' questionnaires are easy to evaluate and are based on observable behaviours. This was the case for the BRIEF questionnaire used in Chapter 4. The adolescent «Interrupts others» or «Does not think before acting» are examples of questions asked. The BIS-11 used to assess impulsivity in adults is composed of items that are more vague and sometimes based on personality traits. The BIS-11 is asks questions as: «I like to think about complex problems», «I am happy-go-lucky», «I am more interested in the present than the future». This could therefore be a possible explanation of the two different results.

Head movements

Another important factor of this thesis that is not yet fully addressed is head movements. Head movements are known to be associated with impulsivity and hyperactivity (Teicher, Ito, Glod, & Barber, 1996). They also proved to be particularly discriminant with clinical populations (Martin & Nolin, 2009; Nolin et al., 2009; Stipanicic et al., 2011; Pierre & Stipanicic, 2012). Similar results were found by Parsons and colleagues (Parsons et al., 2007). Not only did children with ADHD have significantly more errors in the VR-CPT, but they were also looking at distractors in 25% of their missed trials (1% for controls). Additionally, the head movements helped classification of children with vs. without ADHD at a greater percentage than the traditional task could (Adams et al., 2009).

Unfortunately, in this thesis, no head movement data were available. While the equipment used in this thesis was able and ready to record head movements, an error in the program caused the loss of all these data. The lack of head movement data surely diminishes the depth and comprehension of this task. Additional research was done with the VR-Stroop while using a FaceLAB eye-tracker. The results obtained were very promising (Henry et al., 2013). Eye movements tended to decrease over the first half of the task. Participants that showed more errors at the end of the task also showed an increase in eye movements, which could support cognitive fatigue and difficulty in maintaining inhibition throughout the task. More research is here warranted, as typically a decrease in performance over time is associated with clinical populations. This was the case for the experiment conducted by Bioulac and colleagues (Bioulac et al., 2012) with the virtual classroom and ADHD. One hypothesis is that clinical populations would have an even steeper drop in performances on the VR-Stroop over time.

For now, when used without head-tracking data, the VR-Stroop seems to be a measure of inhibition processes with a go/no-go component. This task holds the potential to show greater sensitivity and validity once head movement data are included. Hence, maybe, the full potential of the VR-Stroop is not yet explored.

General limitations

Lastly, some limitations regarding participants should be acknowledged. Participants were mainly Caucasian and had similar socio-demographic characteristics, consequently limiting possible generalization of the results. Second, the recruited samples were obtained on a voluntary basis and may not be representative of the entire population. Further studies including different socio-demographic background, different ethnic groups and possible clinical population are therefore suggested.

Conclusion

The tasks used in this thesis proved to be ecologically valid, while assessing various components of impulsivity. These tasks can easily be controlled and adjusted to a clinician or researcher's need. They are also precise in what they deliver as well as what they measure. They combine the veridical control and rigor of laboratory measures with a verisimilitude that replicates real life situations. One of the main downsides of VR is the lack of empirical or normative data. This might prevent VR from entering clinics and limits where this technology is used, and by whom. This thesis, while validating the tasks used, also provided a possible normative data that could be used by other neuropsychologists in the future.

There is also a need for VRe to be more accessible and affordable. With the demonstration of the usefulness, versatility, validity and sensitivity of VR, this thesis aimed at raising interest for this method of evaluation. To this end, our findings support the use of VR in neuropsychological assessment. Virtual reality can produce stimuli and put participants in environments that have greater magnitude, appeal and meaning than any standard techniques. Its multiple utilities have been exposed in this thesis for both assessment and intervention.

Furthermore, VR was presented as an easy, effective, valid and reliable tool requiring relatively cheap hardware. Technology is also becoming more affordable.

Apparatus such as the Occulus Rift and the Google Glasses are now easily accessible. Also, software such as Unreal, Unity or Half-Life provide easy solutions for individuals who want to develop their own VRe.

The use of VR in neuropsychology is promising. Virtual reality might be viewed as a tool, but it is debatably one of the most powerful and versatile tool the scientific and clinical community has to this day.

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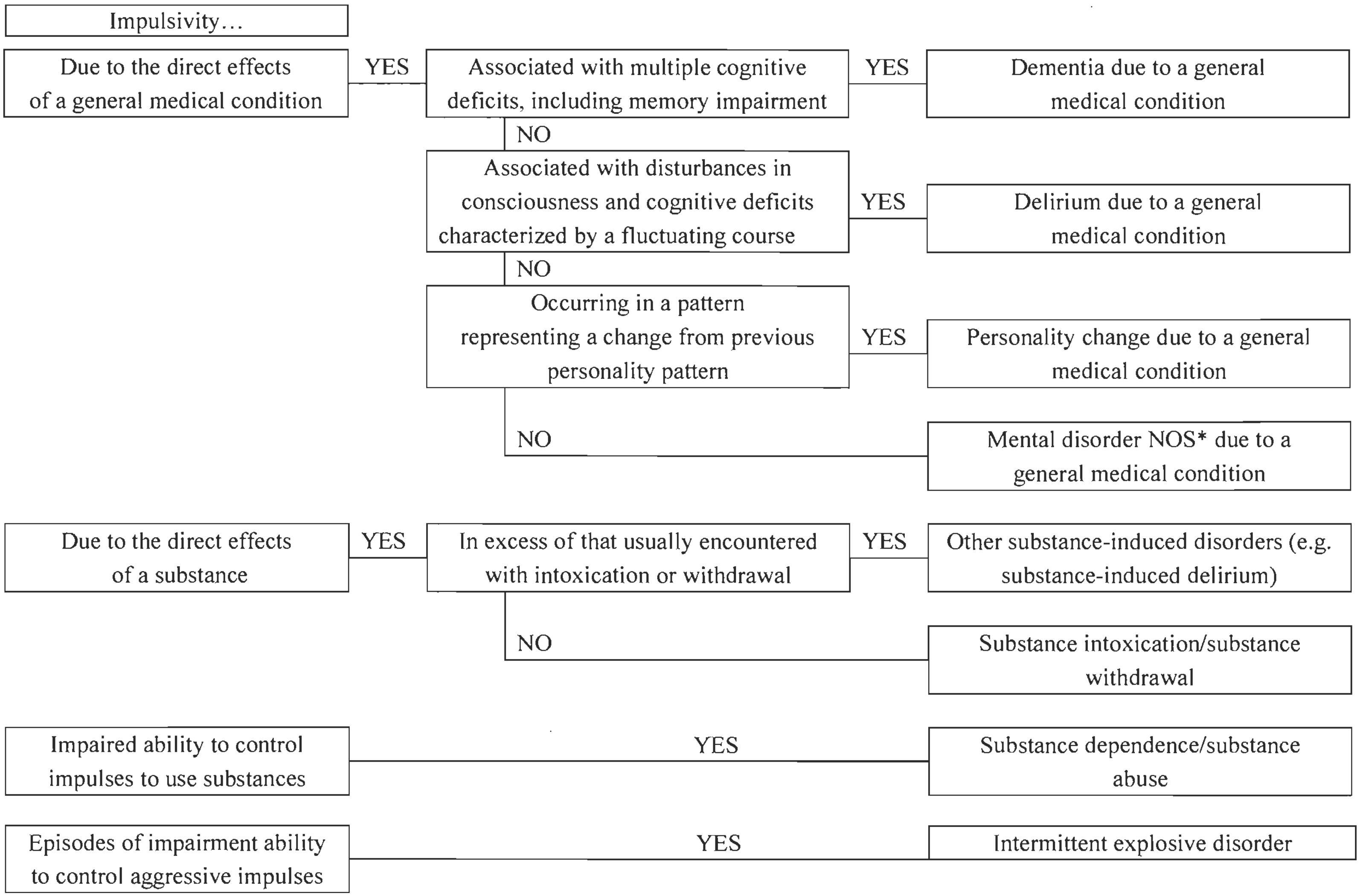
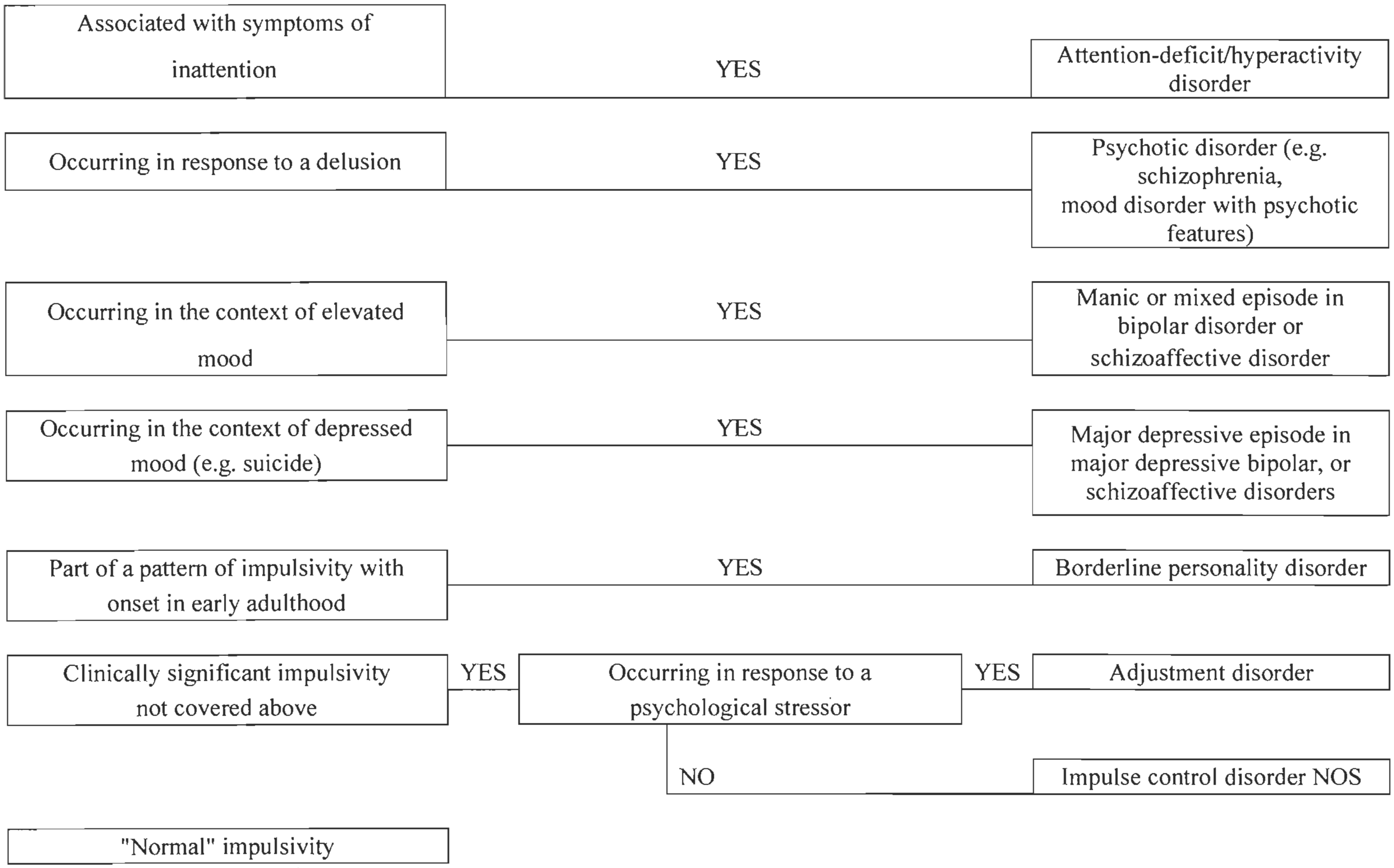
Appendix A
Differential diagnosis of impulsivity


Impulsivity…
Due to the direct effects of a general medical condition
YES
Associated with multiple cognitive deficits, including memory impairment
YES
Dementia due to a general medical condition
NO
Associated with disturbances in consciousness and cognitive deficits characterized by a fluctuating course
YES
Delirium due to a general medical condition
NO
Occurring in a pattern representing a change from previous personality pattern
YES
Personality change due to a general medical condition
NO
Mental disorder NOS* due to a general medical condition
Due to the direct effects of a substance
YES
In excess of that usually encountered with intoxication or withdrawal
YES
Other substance-induced disorders (e.g. substance-induced delirium)
NO
Substance intoxication/substance withdrawal
Impaired ability to control impulses to use substances
YES
Substance dependence/substance abuse
Episodes of impairment ability to control aggressive impulses
YES
Intermittent explosive disorder

Episodes of impairment ability to control aggressive impulses	YES	Intermittent explosive disorder
Episodes of impaired ability to control an impulse to start fires	YES	Pyromania
Episodes of impaired ability to control an impulse to steal objects not needed for personal use	YES	Kleptomania
Episodes of impaired ability to resist the impulse to pull out one's hair	YES	Trichotillomania
Impaired ability to resist impulses to gamble	YES	Pathological gambling
Part of a pattern of antisocial behaviour	YES	Conduct disorder/antisocial personality disorder
Episodes of impaired ability to resist acting on sexual impulses	YES	Paraphilias/sexual disorders NOS
Impaired ability to resist impulses to binge-eat	YES	Anorexia nervosa/bulimia nervosa



*NOS: Not Otherwise Specified

Figure 2. Differential diagnosis of impulsivity. Reproduced from Kay & Tasman, 2006, p. 757.

Appendix B
VR-Stroop task configuration

This section will describe the VR-Stroop task in more details in regards of its conceptualization. First, the pacing of the task will be presented. Then, the scenario use for the VR-Stroop (Apartment) task will be described. The duration and appearance of distractors in the virtual task will be explored. The distractors in both the Virtual Apartment and the Virtual Classroom will then be compared. Then, the spatial location of distractors in the virtual tasks will be presented.

Pacing of the VR-Stroop

The VR-Stroop task is a continuous task where stimuli are presented on a TV screen in the Apartment or on the board in the Classroom. Stimuli appear for 1000ms, followed by a blank screen of a 1000ms. See Figure 3 below for clarification of the pacing of the task. An example of congruent and incongruent stimuli is also presented.

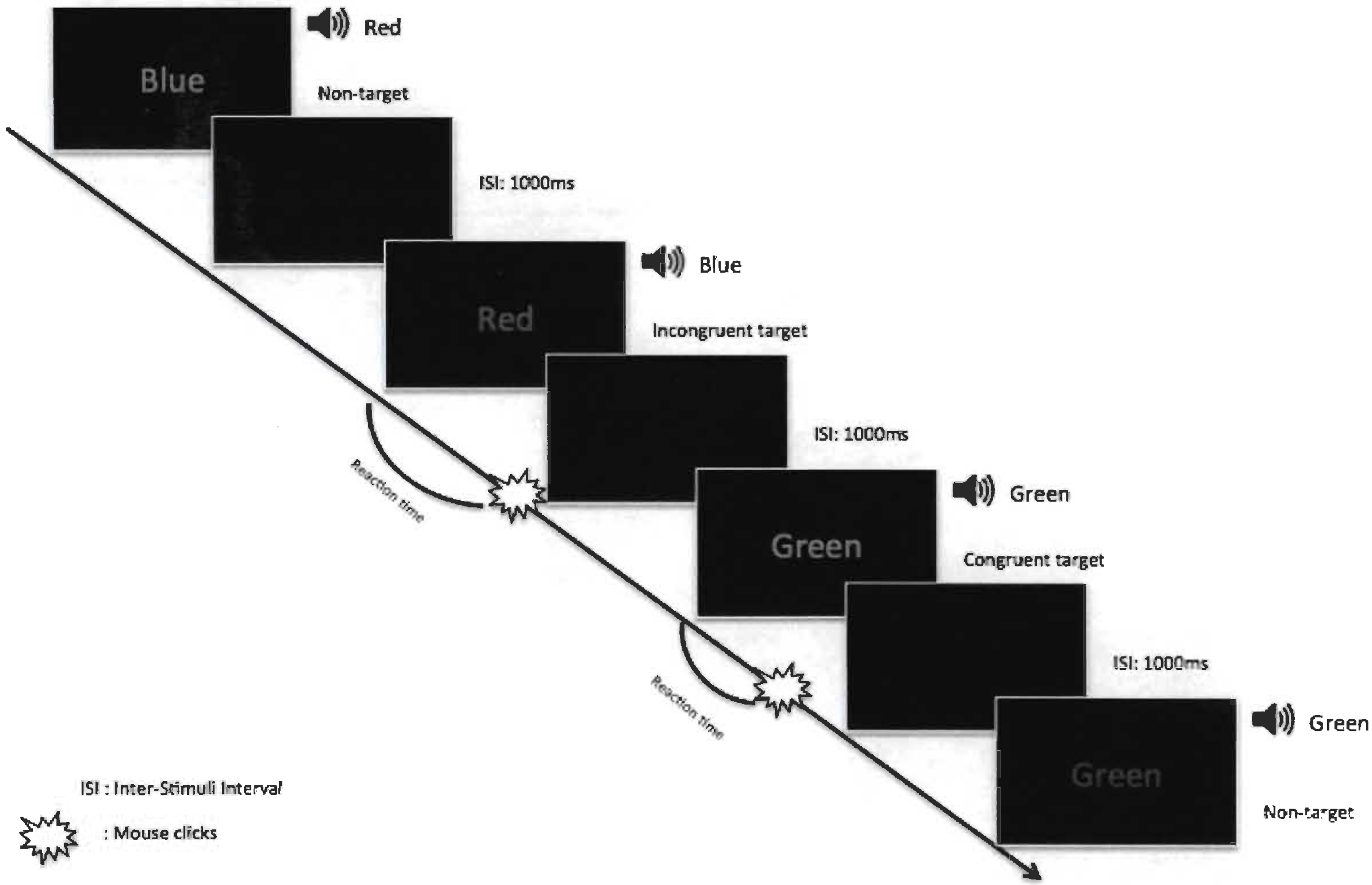


Figure 3. Pacing of the VR-Stroop task.

Scenario of the VR-Stroop

The VR-Stroop task is based on a fixed scenario where predetermined distractors appear at the same time for every participant. This fixed scenario comprises three sections, referred to as a scenario blocks. The task consists of three blocks (block 1, block 2, block 1), which will be described in Tables 9 and 10 below. The start time (in seconds) of each distractor from the beginning of the task will be presented. Their duration (in seconds) and type will also be defined.

Table 9

VR-Stroop-Apartment scenario – Block 1

Stimuli	Start (s)	Duration (s)	Type
Jackhammer	1.0	2.0	Audio
Vaccum cleaner	3.0	9.0	Audio
Answer door	12.0	17.0	Visual
iPhone	29.0	9.0	Audio-visual
Jet noise	31.0	7.0	Audio
Toy robot	38.0	10.0	Audio-visual
Pencil dropped	48.0	1.0	Audio
SUV	49.0	8.0	Audio-visual
Sneeze	57.0	1.0	Audio
Paper airplane	58.0	4.0	Visual
Cat clock	62.0	17.0	Audio-visual
Crumble paper	79.0	9.0	Audio
Schoolbus	92.0	26.0	Audio-visual

Table 10

VR-Stroop-Apartment scenario – Block 2

Stimuli	Start (s)	Duration (s)	Type
iPhone	130.0	9.0	Audio-visual
Crumble paper	144.0	9.0	Audio
Schoolbus	160.0	26.0	Audio-visual
Jackhammer	186.0	2.0	Audio
Paper airplane	193.0	4.0	Visual
Sneeze	197.0	1.0	Audio
Answer door	200.0	17.0	Visual
Pencil dropped	217.0	1.0	Audio

The VR-Stroop Apartment was design to be as equivalent to the Classroom as possible. Also, there has been an attempt to keep an equal balance of audio, visual and audio-visual distractors. When it was not possible to map all the distractors to both environments, a distractor that is similar in nature was used. See Figure 4 below for the list of distractors in both environments.

Virtual Apartment		Virtual Classroom	
Distractor	Location	Distractor	Location
Schoolbus	R	Schoolbus	L
SUV	R	SUV	L
Crumble paper	L	Crumble Paper	L
Pencil drop	L	Pencil drop	L
Paper airplane	L –> R	Paper airplane	L –> R
Drop book	C	Drop book	C
iPhone	C	Raise hand	C
Toy robot	C	Exchange paper	C
Answer door	L	Answer door	R
Cat clock	L	Principal	R
Vacuum cleaner	R	Intercom	R
Jack hammer	R	Bell	R
Sneeze	L	Sneeze	R
Jet noise	C	Jet noise	C

Figure 4. List of distractors in the virtual Apartment and the virtual Classroom.

Spatial location of distractors in the virtual tasks

In this section, the spatial location of the distractors in the virtual tasks will be presented. Table 11 will first attribute a letter to each distractor in the Virtual Apartment, which can later be found in Figure 5. The distractors of the Virtual Classroom will also be described, see Table 12 and Figure 6.

Table 11

Description of the spatial location of distractors in the Virtual Apartment

Letter	Distractor	Location	Type
A	Crumble paper	Left	Audio
B	iPhone	Centre	Audio-visual
C	Toy robot	Centre	Audio-visual
D	Sneeze	Left	Audio
E	Pencil drop	Left	Audio
F	School bus	Right	Audio-visual
G	SUV	Right	Audio-visual
H	Paper airplane	Left to right	Visual
I	Answer door	Right	Audio-visual
J	Cat clock	Left	Audio
K	Jack hammer	Right	Audio
L	Vacuum cleaner	Right	Audio
M	Jet noise	Centre	Audio

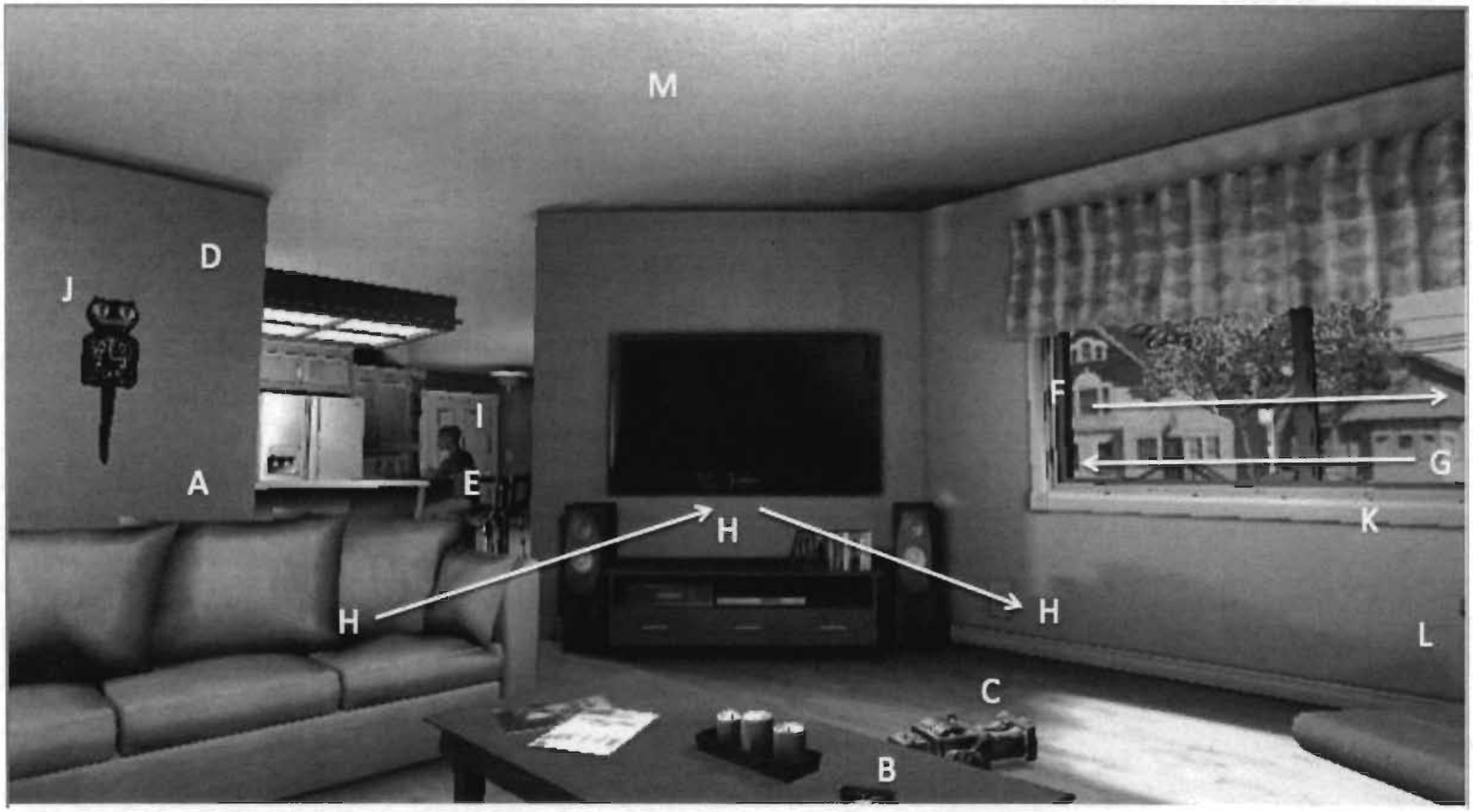


Figure 5. Spatial location of distractors in the Virtual Apartment.

Table 12

Description of the spatial location of distractors in the Virtual Classroom

Letter	Distractor	Location	Type
B	Raise hand	Centre	Visual
C	Exchange paper	Centre	Visual
D	Book drop	Centre	Audio-visual
E	Pencil drop	Left	Audio
F	School bus	Left	Audio-visual
G	SUV	Left	Audio-visual
H	Paper airplane	Left to right	Visual
I	Answer door	Right	Audio-visual
J	Principal	Right	Audio-visual
K	Bell	Right	Audio
L	Intercom	Right	Audio
M	Jet noise	Centre	Audio

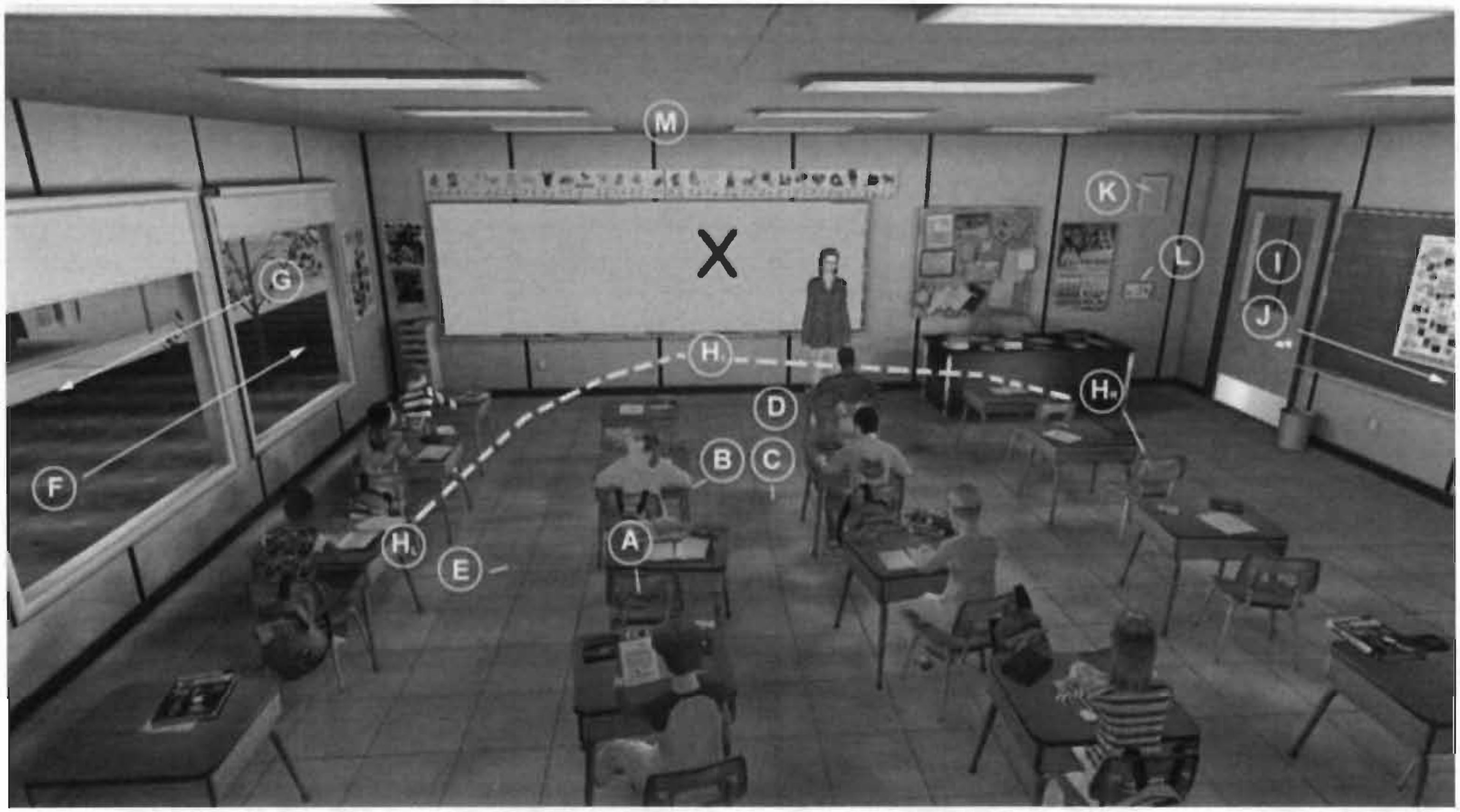


Figure 6. Spatial location of distractors in the Virtual Apartment.

Appendix C
Contributions spécifiques aux différents articles

Article : Henry, M., Jacob, L., & Joyal, C. C. (2015). Évaluation clinique de l'impulsivité. *Revue québécoise de psychologie, 36*(2), 7-30.

Contribution spécifique :

- Recherche et lecture des écrits : 90 %
- Écriture : 70 %

Article : Henry, M., Joyal, C. C., & Nolin, P. (2012). Development and initial assessment of a new paradigm for assessing cognitive and motor inhibition: The bimodal virtual-reality Stroop. *Journal of Neuroscience Methods, 210*(2), 125-131.

Contribution spécifique :

- Planification : 95 %
- Recrutement : 100 %
- Collecte de données : 100 %
- Traitement des données : 100 %
- Analyses statistiques : 90 %
- Écriture : 80 %

Article : Lalonde, G., Henry, M., Drouin-Germain, A., Nolin, P., & Beauchamp, M. H. (2013). Assessment of executive function in adolescence: A comparison of traditional and virtual reality tools. *Journal of Neuroscience Methods, 219*(1), 76-82.

Contribution spécifique :

- Planification : 75 %
- Recrutement : 30 %
- Collecte de données : 80 %
- Traitement des données : 90 %
- Analyses statistiques : 10 %
- Écriture : 20 %